Laboratory
of
Dynamo-Electric
Machinery

NOTES

LABORATORY

OF

DYNAMO-ELECTRIC MACHINERY

FOR THE USE OF STUDENTS IN THE

LOWELL INSTITUTE
SCHOOL FOR INDUSTRIAL FOREMEN

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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LABORATORY OF DYNAMO-ELECTRIC MACHINERY

Notes for Students in the Lowell Institute School for Industrial Foremen.

GENERAL DIRECTIONS.

Protection of Ammeters and Voltmeters. Ammeters are always placed in series with the circuit carrying the current to be measured. They should, therefore, be protected from excessive current due to accidental short-circuit of the line or other cause by being kept short-circuited except when read. All ammeters used in the laboratory must be protected by short-circuit blocks provided for this purpose. One or more of these short-circuit blocks are fastened to each laboratory table. Extra ones may be obtained from the instrument room if needed.

Voltmeters are arranged to be placed directly across the circuit the potential of which is to be measured, and need no protection when the voltage range of their scale is greater than the voltage of the circuit to which they are attached. When, however, a low range scale of a voltmeter is used to measure voltage in a part of a circuit which is supplied through resistance from a source of higher voltage, care must be taken to prevent injury to the voltmeter. If the circuit becomes accidentally opened between the points to which the voltmeter is attached, full line voltage will be put on the instrument, seriously injuring it if not actually burning it out. For this reason a voltmeter which is reading on its low voltage scale should be disconnected as soon as its reading has been recorded. A low voltage scale must never be used without first making sure that the voltage of the part of the circuit across which the voltmeter is to be connected is within its range. The high voltage scale should always be connected before changing to a scale of lower range.

Measurement of Resistance by the Drop of Potential Method. According to Ohm's Law, the current in any part of a circuit not containing a source of electromotive force but carrying a steady current is equal to the ratio of the voltage drop through the part of the circuit considered to the resistance

$$I = \frac{E}{R}$$

Transposing, this becomes $R = \frac{E}{I}$ If, therefore, the resistance of a circuit is desired, it may be measured by passing a known current through the circuit and measuring the potential difference between its terminals.

The ratio of this potential difference to the current will be the resistance. If the resistance to be measured is low, it will be necessary to connect another resistance in series with it to prevent excessive flow of current. In this case the voltmeter should, of course, be connected across *only the resistance which is to be measured and not across the entire circuit.*

If the circuit contains self-inductance, care must be taken to have the voltmeter disconnected when the circuit is made or broken.

Armature circuits and especially field circuits of motors and generators and transformer windings contain self-inductance.

When measuring small resistances, voltmeters with low voltage scales are usually required. These scales, however, *must never be used* until the actual potential across the circuit has been measured on a scale having at least equal range to the voltage of the circuit which supplies the current. If the voltage drop is found to be within the range of the low voltage scale this may be connected. As soon as the voltmeter has been read, the low voltage scale should be disconnected. Many voltmeters are burnt out by failure to take this very simple precaution.

Rise in Temperature by Resistance Measurements. The change in resistance of an electrical conductor with temperature gives a means of determining the increase in temperature in the coils of any piece of electrical apparatus. Thermometers give only the surface temperature. The resistance method gives the average temperature of the wire in the coil. This latter is, of course, what is usually desired. The temperature rise due to load in electrical apparatus should when possible be found by the resistance method.

If R_0 is the resistance of any metal conductor at zero degrees centigrade and R_t is its resistance at the temperature t

$$(1) \quad R_t = R_0 (1 + Bt)$$

when B is the mean temperature coefficient of the conductor between zero degrees and the temperature t.

B for copper is 0.00428. Replacing B by this value, equation (1) becomes for copper.

$$(2) \quad R_t = (1 + 0.00428\,t)\,R_0$$

The resistance at any other temperature greater than t, as for example $t + \theta$ is

$$(3)\ R_{(t+\theta)} = \left\{ 1 + 0.00428\,(t+\theta) \right\} R_0$$

Combining equations (2) and (3) and solving for θ gives

$$(4)\ \theta = (233.8 + t) \left\{ \frac{R_{(t+\theta)}}{R_t} - 1 \right\}$$

which is the equation for calculating the temperature rise in elec-

trical apparatus recommended in the Standardization Rules of the A. I. E. E.

Equation (4) gives the rise in temperature, θ, above the initial temperature, t, or the room temperature.

The temperature rise measurements in all pieces of electrical apparatus should be made as nearly as practicable at a room temperature of 25° centigrade.

When measuring resistances for use in calculating the increase in temperature, care must be taken not to include any resistance which does not belong to the circuit in which the temperature rise is to be found. If the resistance is to be measured by the drop of potential method the voltmeter leads must be placed directly on the terminals of the circuit. For example, when determining the temperature rise in an armature of a motor or generator, the voltmeter leads must be placed on the commutator and not on the terminals of the armature circuit. Similarly in the case of a field, the voltmeter leads must be placed directly across the terminals of the field coils inside of any rheostat or other resistance which may be in the circuit.

The resistance of the different paths through the armature will necessarily vary slightly. In order to eliminate this variation in resistances used for temperature rise, the hot and cold resistance must be measured with the armature in exactly the same position.

The ends (not the surface) of the commutator bars which are under a pair of brushes during the cold resistance measurement should be marked and the same bars brought under the same brushes for the hot resistance measurements.

Resistances for temperature rise must always be taken with great care if reliable results are to be obtained.

Temperature by Thermometer. When a thermometer is used to measure the temperature of any part of a motor or generator, the bulb should be in contact with the part the temperature of which is to be measured. In order that the thermometer may give more nearly the temperature of the part which it touches, the thermometer bulb should be protected by a piece of putty or a small pad of cotton waste.

Measurement of Speed. The simplest method of measuring the speed of any motor or generator is by means of one of the many forms of hand revolution counter which may be inserted in one of the conical center holes which will always be found in the ends of motor or generator shafts. With a little care perfectly satisfactory results may be obtained in this way.

When a number of readings of speed are required and particu-

larly when any definite speed has to be maintained or produced, some form of direct reading tachometer is desirable.

There are many forms of tachometers on the market. They nearly all depend upon some form of centrifugal device which acts through the gears on a pointer. Some of these tachometers are very satisfactory but they all require occasional calibration and are expensive.

A comparatively inexpensive form of tachometer which is quite satisfactory consists of a small magneto generator driven from the shaft of the machine the speed of which is to be determined. If a voltmeter, preferably of high resistance, is attached to a magneto, its reading will be directly proportional to the speed. The voltmeter and magneto must be calibrated by keeping the voltmeter reading constant and measuring the speed by an ordinary revolution counter. Several sets of readings should be taken and averaged. If s is the speed in r. p. m. and v the corresponding voltmeter reading; $v = ks$, from which the constant k may be determined. If the range of speed over which the magneto is to be used is large, it should be calibrated at a number of different points. These points should cover the entire range of speed. If any sign of variation of the constant k is found, a plot should be made between speed and voltage and the speed corresponding to subsequent voltmeter readings taken from the plot. Even if k shows no sign of variation, a plot, which in this case will be a straight line, will be convenient.

All magnetos as well as other forms of tachometers absorb some power. This, however, can usually but not always be neglected. When used on small machines a correction for the power absorbed often has to be applied. The small magnetos used in the laboratory absorb about six to ten watts at 1000 r. p. m. The larger size require from two to three times this to run them.

Measurements of the Mechanical Output of a Motor. The output of any motor is equal to the force exerted at the pulley multiplied by the distance travelled by the circumference of the pulley in a minute.

If r is the radius of the pulley in feet and n the revolutions made by it per minute, the output in h. p. will be

$$\frac{2\pi\, r\, n\, F}{33000}$$

when F is the force in pounds exerted at the circumference of the pulley.

Fr = T is the moment of the couple exerted by the pulley or the torque developed by the motor in pound-feet.

If this torque is measured the output may easily be calculated.

In order to measure the torque, some form of friction brake is necessary. There are many forms of brakes but these differ only in details.

One fairly satisfactory brake is shown in Fig. 1.

abc is a friction band passing around the pulley. The turning moment or torque is measured by the difference of pull exerted at *a* by the spring balance B and at *c* by the weights W acting through the lever arm *cde*.

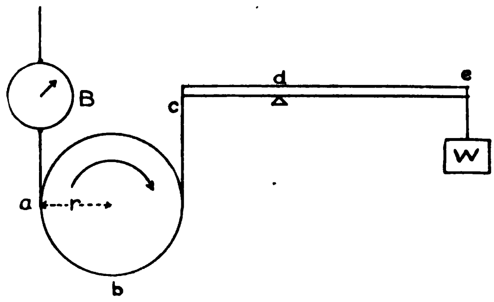


Fig. 1

The load is varied by changing the tension of the band *a b c* by altering the weight at W. The pulley must revolve in the direction of the arrow or towards the spring balance.

$$\text{Torque} = \left\{ W\frac{de}{cd} - B \right\} r$$

Another convenient form is shown in Fig. 2.

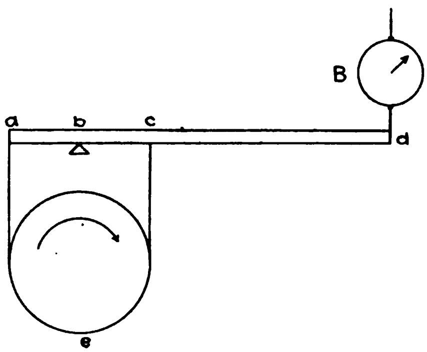


Fig. 2

A lever arm *a d* is supported at *b* on a knife edge. The belt *a e c* is fastened to the points *a* and *c* each at a distance from *b* equal to the radius of the pulley.

The torque exerted by the pulley is balanced by the couple produced by the reaction of the pivot *b* and the upward pull of the spring balance at *d*. A knife edge must, of course, be used at *d*.

$$\text{Torque} = B \times b\,d$$

If the distance *b d* is made one foot, the balance if graduated in pounds will read the torque directly in pound-feet. The load is varied by changing the tension of the brake band by raising or lowering the pivot *b*.

A third form of brake which is satisfactory and somewhat less expensive than those given in Fig. 1 and 2, is shown in Fig. 3.

In this brake a wooden arm $a\ d$ has a wooden shoe, which fits the brake pulley, attached to one end. A piece of heavy cotton belting passes under the drum and is attached to a fixed hook at e and hooks on the end of a screw at f. A spring balance is attached to a knife edge at a.

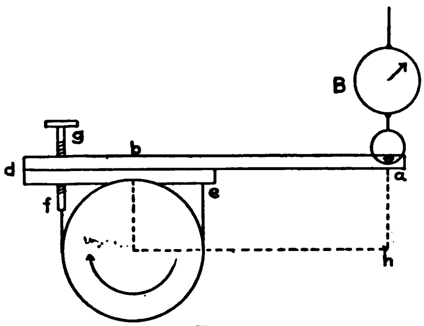


Fig. 3

The load is varied by changing the tension of the belt by means of the screw g. The torque, B × $a\ b$, is the balance reading multiplied by the horizontal distance between the knife edge a and a vertical line through the center of the pulley.

In all forms of brake involving the use of an arm, the arm must be kept in a horizontal position provided, of course, the balance exerts its pull vertically.

The lever arm used in the brake shown in Fig. 1 must have a counter weight so that it may be balanced. This balancing should be done with no weights in the pan at W and with the brake band hanging free from the pulley.

The lever arms in the other two forms of brakes need not be balanced. The unbalancing, however, must be such as to cause the end to which the spring balance is attached to be slightly too heavy.

All spring balances used in connection with brakes must be corrected not only for their zero errors but also for any pull exerted on them by the brake arm or band when the motor is not running.

The combined zero reading of the balance and brake for the brakes shown in Fig. 1 and 2 should be found by loosening the band until it hangs entirely free from the drum. The deflection of the balance under this condition will be its zero reading plus the zero reading of the brake. This zero reading must be subtracted from all subsequent readings.

The zero reading for the brake shown in Fig. 3 may be found in two different ways. For either, the brake band must hang entirely free from the pulley but must not be disconnected from the lever arm.

First method.—Turn the pulley or drum by hand very slowly until the brake shoe just slips. At this instant read the spring balance. Repeat, turning the pulley in the other direction. The mean of the two balance readings will be the zero reading of the brake.

Second method.—Lift the brake shoe and place a small piece of round metal rod between the shoe and drum directly over the

centre of the drum, and with the arm in a horizontal position read the spring balance. This will be the zero reading. If a round piece of metal is not available a round (not hexagonal) pencil may be used.

All forms of brakes require special drums. Ordinary pulleys cannot be used as there is no means by which these can be kept cool. Unless artificially cooled, brake drums will become intensely hot and ruined. Moreover, heat will be transmitted through the shaft to the bearing and the bearing also injured.

The usual means of cooling a brake drum is by keeping a film of water on the inside of its friction surface. This water, which keeps the drum cool by its evaporation, is retained by making the drum as indicated in cross section in Fig. 4.

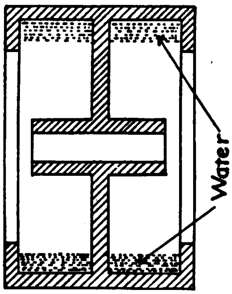


Fig. 4.

Holes must be bored through the central flange near the circumference of the pulley to permit the passage of water from one side to the other.

The water will rapidly evaporate and must be replenished frequently. In replenishing it care must be taken not to wet the friction band. A large quantity of water should not be kept in the drum as it is apt to produce unbalancing.

A brake of the type illustrated in Fig. 3 with a two foot arm and a drum 12 inches in diameter with a shoe and cotton brake band 4 inches wide will easily absorb fifteen to twenty horse-power at a pulley speed of 1000 r. p. m.

Wattmeters.—A wattmeter always consists of two separate parts; an ammeter or current coil, and a voltmeter or potential coil. The ammeter coil is placed either directly in one of the mains of the circuit of which the power is to be measured or short-circuits the secondary coil of a current transformer which has its primary in one main. In this latter case, the ammeter coil carries a current which is always proportional to the main line current and the reading of the wattmeter must be multiplied by a proper constant. Current transformers are seldom needed for currents below 50 amperes except on high-tension lines, where they are used to insulate the instruments from the line voltage. In such cases potential transformers are also required to insulate the potential coils of the wattmeters from the line voltage. When both current and potential transformers are used, one end of the current coil of the wattmeter should be connected to one end of the potential coil and then grounded.

Shunts cannot be used with any instruments intended for use on alternating current circuits except hot wire ammeters.

There is always a large non-inductive resistance in series with the potential coil of a wattmeter. This resistance with the potential coil is placed in shunt across the line. Most of the drop in potential in this shunt circuit occurs in the series non-inductive resistance. In order, therefore, to keep the potential coil and the current coil of any wattmeter at the same potential, the end of the potential coil and not the end of the series resistance must be connected to the line containing the current coil. This precaution is especially important when power in circuits of high voltage is to be measured, and if not observed, there will be great danger of breaking down the insulation between the two coils and burning out the instrument. Even if the instrument is not burned out the static attraction between the current and potential coils due to their difference of potential may cause false deflections.

When there is no diagram with a wattmeter showing its proper connections, the binding post of the potential-coil circuit which is marked zero should be connected to the line containing the current coil. The free terminal of the series non-inductive resistance which for voltages up to 150 volts, and sometimes up to 300 volts, is in the base of the instrument, is connected to the binding post marked with the potential limit. This is the post which should be connected to the line not containing the current coil. When it is necessary to extend the voltage range of a wattmeter by placing additional resistance in the potential-coil circuit, this resistance must be connected to the terminal on the instrument marked with the voltage limit. Such a resistance is called an extention coil or multiplier. When an extention coil is used with a wattmeter, all the readings of the instrument must be multiplied by the proper constant. Extention coils are seldom used to increase the voltage range beyond 500 volts. For voltages above 500 transformers are used.

The correct connections for a wattmeter are shown in Fig. 5. and are indicated diagramatically in Fig. 6.

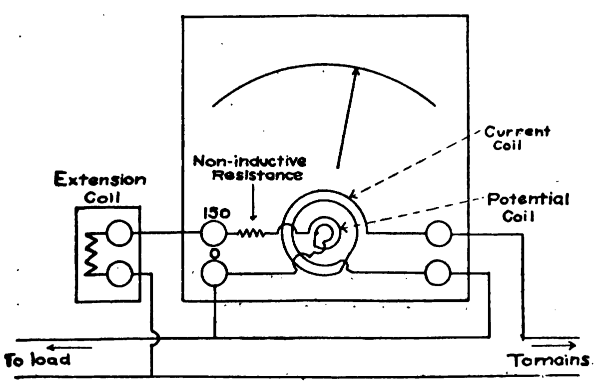


Fig. 5.

A is the current coil. V is the potential coil for convenience shown outside of the current coil. R is the non-inductive resistance in series with the potential coil including the resistance of the extention coil in case one is used.

If a wattmeter reads backwards, the current coil should be reversed and not the potential coil. Reversing the potential coil circuit will make the potential difference between the two coils equal to line potential.

The free end of the potential coil a may be connected to a as shown or may be connected to b. If connected to a, the wattmeter not only measures the power consumed by the load but also measures the power absorbed by the voltage coil of the wattmeter.

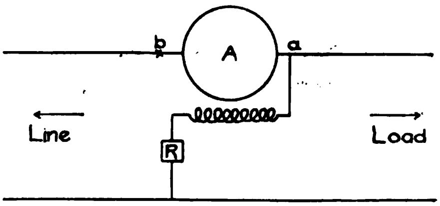


Fig. 6

This is equal to $\frac{V^2}{R}$ where V is the potential of the circuit and R is the total resistance of the potential coil and its series resistance. This resistance is usually given on the instrument or its box. If a is connected outside of the current coil or to b, the wattmeter will record the power delivered to the load plus the I^2R loss in its current coil. A wattmeter always registers the power consumed in one of its coils but *never* the power consumed in both.

The correction for the heating loss in a wattmeter may amount to five or six per cent, and in exceptional cases to even ten per cent of the power recorded, but in commercial work as a rule, except when low range instruments are used or instruments reading on very low power-factor, corrections for heating losses are unnecessary. They should, however, never be overlooked. In core-loss measurements on transformers, corrections are usually necessary.

The size of a wattmeter can never be determined simply by the number of watts to be measured. It must always be fixed by the current and the voltage of the circuit irrespectively of the power, for the coils of a wattmeter cannot stand more than a certain current without becoming overheated and burned out. Therefore the current rating and voltage limit, which are always marked on a wattmeter, should never be exceeded. If the power-factor is low, the scale deflection also will be unavoidably low, but nothing can be done except to make the best of it. The use of an instrument with a lower range current coil would result in burning it out.

In selecting a wattmeter for use on low power-factor, it is important that one be chosen which will be used at as nearly as possible its full current and voltage ratings.

Since a wattmeter never indicates the current it is carrying or the voltage impressed upon its potential coil, it is always necessary to protect a wattmeter by an ammeter and a voltmeter. Quite frequently corrections have to be applied to the wattmeter readings for the power consumed by the heating in these instruments.

The current coil of a wattmeter should be treated as an ammeter and should, therefore, be protected by a short circuit block.

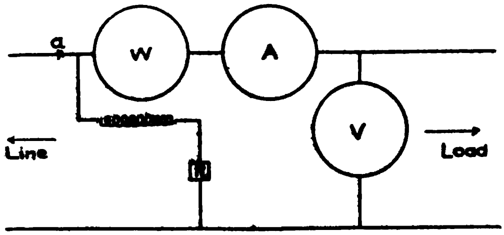


Fig. 7

The proper grouping of a wattmeter, an ammeter, and a voltmeter for measuring the power delivered to a load is shown in Fig. 7.

The voltmeter should always be placed next to the load, as in this position only will it give the correct voltage. If it is placed outside of the wattmeter at *a* it will read too high by the impedance drop through the ammeter and wattmeter current coil.

This impedance drop usually will be negligible but in case it is not, correction for it cannot be made as the impedances of the instruments are not known.

The ammeter placed as shown between the voltmeter and wattmeter will read too high by the voltmeter current. Correction for this, however, can be applied if necessary. Since the voltmeter circuit is nearly non-inductive, the current taken by it will be its reading divided by its resistance. The ammeter should be corrected vectorially for this current. Except when the current to be measured is small, this correction is negligible.

If W, A and V represent the readings of the instruments and R_w, R_a and R_v the resistances of the wattmeter current coil, the ammeter, and the voltmeter respectively, the true power, current, and voltage of the load are given by the following expressions.

True power =

$$W - A^2R_w - A^2R_a - \frac{V^2}{R_v}$$

True current =

$$A - \frac{V}{R_v}\text{(vector subtraction)} = \sqrt{A^2 + \frac{V^2}{R_v^2} - 2\frac{W}{R_v}}$$

True Voltage = V.

NOTE:—The expression for the true current is derived from the solution of the vector triangle formed by the true current, the ammeter current, and the voltmeter current.

If the electrical output of any piece of apparatus is desired, the connections shown in the previous diagram are correct, provided what is marked load on the diagram is assumed to be the apparatus delivering the power. The corrections in this case will be additive.

Measurement of Power in Three-phase Circuits.—The power in any three phase circuit may be measured by either the three or the two wattmeter method.

The proper connections for the *three-wattmeter method* are shown in Fig. 8. The three wattmeters must have potential coil circuits of the same resistance in order that *a* will be the true neutral point of the system. The voltage limit of the potential coils should be at least equal to the voltage between the lines divided by the square root of three. The numerical sum of the three wattmeter readings will give the true power in the circuit under all conditions of balance and power factor. The power factor of an unbalanced three phase circuit is meaningless. If the circuit is balanced or nearly balanced the power-factor is given by

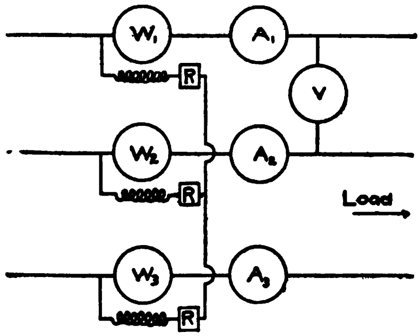


Fig. 8

$$\frac{W_1 + W_2 + W_3}{\sqrt{3}\ I\ V}$$

where I is the average line current and V is the average line voltage. If the voltage of the circuit is not exactly balanced, the voltmeter should be placed across the three phases in succession in order that the average voltage may be obtained. If the load is balanced two of the wattmeters may be omitted and their potential coils replaced by equivalent resistances. Three times the reading of the remaining wattmeter will give the power in the three phase circuit. A box containing the equivalent resistances is known as a Y box.

The proper connections for the *two-wattmeter method* are given in Fig. 9. The two wattmeters used in this method need not be similar in construction and resistance. Their current and voltage rating should, however, be the same. The voltage limit of the potential coil circuits must be equal to, or slightly greater than the voltage between the lines. The algebraic sum of the readings will give the true power in the circuit under all conditions of balance and power-factor provided the circuit does not contain a neutral wire which extends back of the point at which the power is measured. The readings of the two wattmeters will not be equal even for balanced

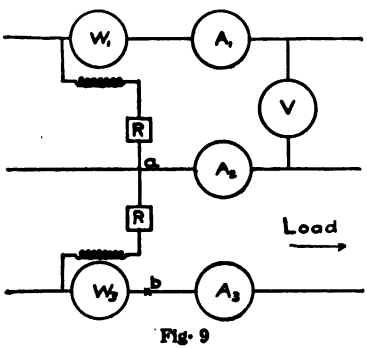


Fig. 9

loads except for system power-factors of unity and zero. Zero power-factor for the system will, of course, never be reached. For power factors above 50 per cent both wattmeters will read positively and their readings should be added. Below 50 per cent power-factor, one wattmeter will read negatively and the true power will be the difference of the readings. The readings of both wattmeters will be positive if both wattmeters are similarly connected. If the connections of the current coil of one have to be reversed with respect to the connections of the current coil of the other in order to make both wattmeters read up scale, the reading of the wattmeter with the lesser reading should be marked negative and subtracted from the reading of the other. If the two wattmeters are of the same make and type, simple inspection will be sufficient to determine whether their connections are similar or dissimilar. If the two wattmeters are not alike, the easiest way to determine similar connections of the two instruments is to put both wattmeters in the same circuit and note the connections of the current coils which give up scale deflections. If the load on the circuit is nearly balanced there is a very simple method by which the sign of the wattmeter readings may be found. If either wattmeter is reading negatively it will be the one with the lesser deflection. Disconnect the potential coil of this wattmeter from *a* (see diagram) and connect it to the third line at *b*. If the direction of the deflection reverses, it was reading negatively. This method cannot be relied upon if the circuit is badly out of balance.

Plots.—The most convenient method of showing the performance of any piece of electrical apparatus is by means of a plot of its characteristic curves. Usually, all of the characteristic curves of any motor or generator can be put on a single sheet, but judgment must always be used in arranging the curves in order to prevent confusion. The intersection of two or more curves on the same sheet should be avoided when possible. Curves which have nearly the same slope should not be permitted to cross. Students should consult some of the trade bulletins in order to familiarize themselves with the customary method of arranging plots of the characteristic curves of electrical apparatus.

Scales.—A good general rule to be followed in selecting a scale for a plot is to use a scale which will permit plotting, by estimation, of tenths or fifths between the smallest divisions on the plotting paper, the last figure retained in the data. For example:—The voltage of a 110 volt circuit would probably be measured by a voltmeter with 150 divisions, each representing one volt. This voltage would be read to one-tenth of a volt. In plotting this data, the tenths volts would be plotted by estimating tenths of volts between the smallest divisions on the plotting paper. The above rule cannot be rigorously followed, but it should not be deviated from except for some good cause as, for instance, in order to im-

prove the slope of a curve or to better the arrangement of the curves on a plot.

Nothing but decimal scales should be used. Scales divided into quarters, thirds, sixths, etc., must be avoided. They are extremely inconvenient in plotting and are very difficult to read.

In Figs. 10 and 11 are given some examples of both good and bad scales.

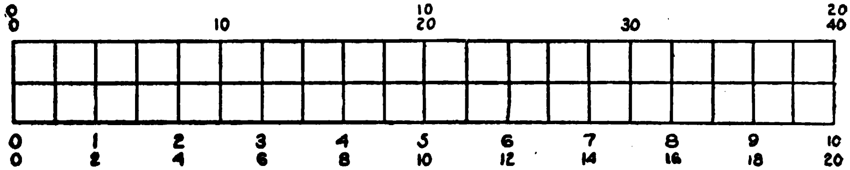


Fig. 10.—Good Scales

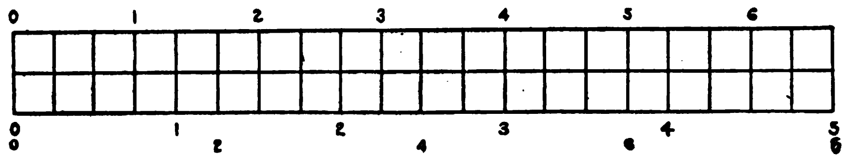


Fig. 11.—Bad Scales

Except in the cases noted below, the zero points of all scales used on any plot should be placed at the origin of the axes of coordinates.

The zero points of scales for plotting quantities which show only small variation ; as for example, the potential of a compound generator or the speed of a shunt motor, need not be placed at the origin or even on the plot at all provided a better arrangement of the curves can be obtained by placing the zeros elsewhere.

The numbers for the scales on any plot and what these numbers represent, should be placed along the margins. Plotted lines must be marked in such a way that they can easily be identified. Sufficient data should also be placed in one corner of a plot to identify completely the apparatus for which the plot is made. In case of a motor or generator this data should include the name of the manufacturer, the type, the rating, and the serial number of the machine.

Due to errors of observation and to the impossibility of maintaining perfectly constant conditions during any test, plotted points will very seldom lie exactly along a smooth line. Smooth lines, however, should always be drawn. These lines should be placed so as to best represent the plotted points, and should be so drawn that the points will be distributed about equally on their two sides.

Lines should be sketched in lightly with a pencil and then, after their best shape and position has been determined, they should be gone over with ink, using French curves. The plotted points should not be erased.

The Number of Figures to be Retained in Data.—The number of figures to be retained in data should always be determined by the reliability of the measurements. The retention of unnecessary figures is not only misleading, but absolutely misrepresents the accuracy of any piece of work. A good general rule for ordinary engineering work is to reject all figures in final results beyond the first place in which variation occurs. For example, suppose a current of 50 amperes is to be read on an ammeter having one hundred divisions, each division representing one-half an ampere. If the conditions of the circuit are sufficiently constant to permit reading tenths of division, the figure in the first place after the decimal point should be retained. If this happens to be zero it should not be omitted. The current in this case should be written 50.0 and not simply 50. If the conditions of the circuit were so variable that the ammeter could not be read closer than five amperes, the current should be recorded only to the nearest five amperes. In the mean of a considerable number of single observations, one more figure should always be retained than is kept in the single observation.

If two or more quantities having different accuracies are multiplied or divided, the number of figures retained in the result should be determined by the least accurate of two quantities. For example:—If the input to a motor is given as 51. amperes at 110.3 volts, the calculated input in watts should be written 56000 watts and not 56253 watts. If the first figure rejected is five or greater, one should be added to the figure next preceding.

Slide Rule.—The ordinary ten-inch slide rule, if used with care, ought to yield results, in this case of simple computations, which are reliable to about one half of one per cent. Used carelessly, however, or without discretion, the slide rule will give results which are *absolutely* worthless.

When an accuracy greater than one half of one per cent is desired, logarithms must be resorted to. Even when this accuracy is desired, the slide rule may still be used for parts of the computation as, for instance, correction terms, where often an error of three or four per cent, or sometimes even ten per cent will scarcely affect the result.

Slide rule computations are accurate enough for most engineering work, but efficiencies which are calculated from direct measurements of the losses in any piece of high efficiency apparatus will usually warrant the use of logarithms. Even in these cases the slide rule is usually sufficiently accurate for computing the losses.

If L is the total losses in a transformer under any assumed output, the efficiency will be

$$\frac{\text{Output}}{\text{Output} + L}$$

If L is 4 per cent. of the output the numerical value of the efficiency will be

$$\frac{100.0}{100.0 + 4.0} = \frac{100.0}{104.0}$$

An error of one part in forty or 2 1-2 per cent in the losses will effect the efficiency only by about 0.1 of 1 per cent. In a case of this kind, the accuracy of the slide rule is amply sufficient for the calculation of the losses. Logarithms should, however, be used in the computation of the ratio of output to the input.

Losses in Motors, Generators and Transformers.—In order that students may have something on which to base their estimates of sizes of instruments required for any experiment, the following tables have been arranged giving the average efficiency, losses, etc., of motors, generators, and transformers of normal design.

In making use of these tables it must be borne in mind that they give only averages for machines of normal design, and that the values for any particular machine may differ considerably from those given in the tables. The largest variations will occur in the distribution of the losses, where a difference of fifty per cent would not be unusual.

TABLES OF LOSSES

In

Motors, Generators and Transformers

SHUNT MOTORS.

Efficiency and Distribution of Losses at Full Load.

Rating horse power	Efficiency %	Total Losses watts	Armature I^2R Loss %	Stray Power Loss %	Field Loss %
1	74.5	250	6.0	14.5	5.0
2	76.5	450	6.0	13.0	4.5
5	80.0	940	5.5	10.5	4.0
10	84.5	1370	5.0	7.0	3.5
15	86.5	1760	5.0	5.5	3.0
25	89.0	2300	4.2	4.0	2.8
50	90.5	3950	3.7	3.5	2.3
100	91.5	6900	3.5	2.8	2.2

SHUNT GENERATORS.

Efficiency and Distribution of Losses at Full Load.

Rating kilowatts	Efficiency %	Armature I^2R Loss %	Stray Power Loss %	Field Loss %
1	74.0	6.0	15.0	5.0
2	77.0	5.8	12.7	4.5
5	81.5	5.5	9.3	3.7
10	85.5	5.0	6.5	3.0
15	87.5	4.8	5.1	2.6
25	89.5	4.2	3.9	2.4
50	91.0	3.6	3.2	2.2
100	92.0	3.2	2.8	2.0

Resistance of series field of compound winding = 1-8 to 1-4 resistance of armature.

TRANSFORMERS.

60 Cycles.

Rating kilowatts	Efficiency 100% p.f.	Copper Loss watts	Core Loss watts	Exciting Current % of Load Current
2	96.0	40	40	6.0
5	96.8	90	70	3.0
7.5	97.2	115	95	2.3
10	97.5	140	110	2.0
25	98.0	290	210	1.2
50	98.3	475	375	.8
100	98.4	900	700	.4

I

RESISTANCE MEASUREMENTS OF ARMATURE AND FIELD

The resistance of a generator armature is of a comparatively low value and varies with the capacity of the machine. Machines of 1 kw. rating may have a resistance of one or two ohms while the armature resistance of a 25 kw. machine may be about one-tenth of an ohm. The resistance of armatures of large machines will be still smaller, decreasing with an increase in size.

The value of field resistance varies with the capacity of the machine in this same way, from one hundred ohms for the 1 kw. machine down to twenty ohms for the 25 kw. machine.

These resistances are also functions of the machine voltage. With two machines of equal rating the one designed for a higher voltage will have the larger armature and field resistances.

An auxiliary resistance is always necessary when measuring the resistance of the armature or series field of a motor or generator. It is not necessary in the case of the shunt field providing the line voltage does not exceed the rated voltage of the machine under consideration.

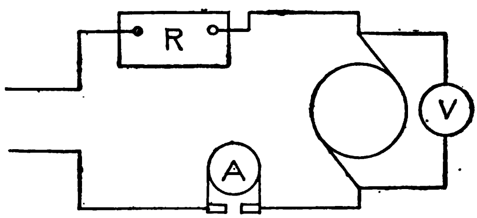


Fig. 12

Test.—Connect the armature of the machine to be tested to the mains in series with a rheostat and ammeter of proper size. Attach a voltmeter to the armature terminals outside of the brushes. Vary the current by means of the rheostat and read the voltmeter for values of current from 0.25 rated current to 1.25 rated current recording readings for five or six steps.

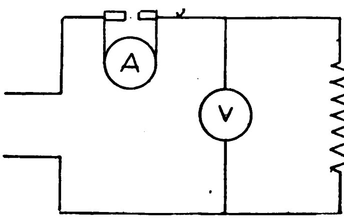


Fig. 13

Connect the field in series with an ammeter across a line of proper voltage and record voltage and current.

In the final report plot a curve between armature resistance and current.

II

DIRECT-CURRENT GENERATOR CONNECTIONS

The shunt field of a direct current generator may be either separately or self-excited. When the field is separately excited, the generator will develop voltage for either polarity of field and either direction of rotation. When the field is self-excited the generator may not develop rated voltage for the following reasons:—(See pages 1 and 2 for precautions to be observed in the use of voltmeter and ammeter.)

1. Residual magnetism is absent.
2. Field resistance is too high.
3. Machine is not running at its rated speed.
4. Improper connection of the field for the direction of rotation.
5. Brushes are improperly placed.

When the generator is being driven in a certain direction the proper connection of the field is fixed. The generator will not deliver voltage for the reverse field connection as long as it is revolving in that direction. Reversal of the direction of rotation on the other hand will necessitate the reversal of the field or the machine will not build up to voltage.

A reversal of residual magnetism will result in a reversal of the generator polarity.

Test:—Connect the shunt field of the generator to be tested to the laboratory mains through a field rheostat of the proper resistance and current capacity.

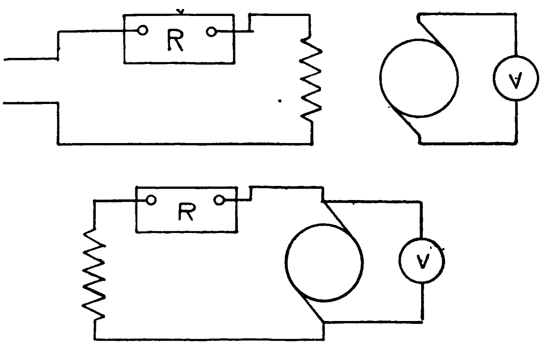


Fig. 14

Record the voltages across the armature when the generator is being driven at rated speed and at half speed with field adjusted for maximum flux, brushes being set for maximum voltage. Reverse the field connections and repeat, being careful to record the polarity in each case.

Disconnect the field from the mains and note the direction of the voltage produced by the residual flux.

Connect the field to the armature and vary the amount of resistance. Note the polarity of the armature and record the voltage for decreasing resistance in the rheostat.

Reverse the field and repeat.

Reverse the direction of rotation and repeat the last two runs.

Tabulate all the results in the final report and explain the results.

III

POTENTIAL ABOUT THE COMMUTATOR

There are several methods by which the variation of the potential about the commutator of a generator or motor may be determined. The one which will be used in this experiment employs a single pilot brush. Starting from either the positive or the negative brush on the motor or generator, this method adds the potentials produced in the motor or generator armature coils from the starting point up to any point in the field.

The fields of the generator to be tested should preferably be disconnected and separately excited, i. e., excited from some external source. The armature should be driven at a constant speed.

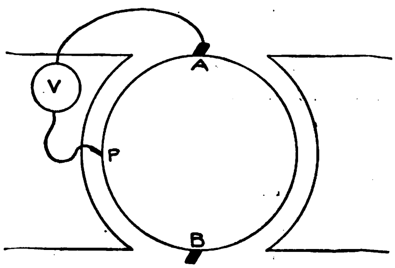


Fig. 15

One terminal of a voltmeter is attached to one brush, A, of the generator (the negative brush is generally chosen), the other terminal is attached to a small movable pilot brush, P, which can be moved about the commutator. If the pilot brush is placed at A, the two brushes will be at the same potential and the difference of potential between them will be zero. If the pilot brush is moved to B, the potential difference between it and A will be a maximum and equal to the potential of the generator. If now, P, starting at A, is slowly moved about the commutator, the reading of the voltmeter will gradually increase and will become a maximum when P reaches B. It will then decrease and finally become zero again when P gets back to A.

It is often convenient to plot the potential between A and the pilot brush radially outward from a circle which represents the commutator.

Such a plot is shown in Figure 16.

The result may also be plotted in the ordinary way, in which case the curve will be similar to Fig. 17.

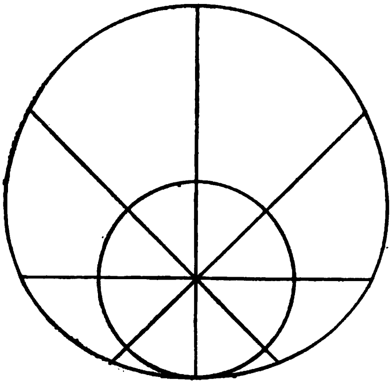


Fig. 16

The steepness of the different parts of this last curve shows the relative activity, or idleness, of the armature coils when in different positions with respect to the field. The potential of a coil is a minimum, or zero, when it is at right angles to the field at 0° or 180° and should be a maximum when parallel to the field or at 90° or 270°. This is shown in the second figure by the flatness of the 0° and 180° points and the steepness of the 90° and 270° points. Curves of this sort serve to show the best position for the brushes as well as the distribution of the flux in the air gap.

If potential curves are also taken when the armature delivers current, the effect of the armature reaction may be studied from the distortion produced.

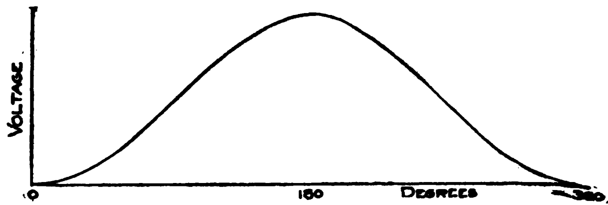


Fig. 17

Test.—Separately excite the fields of the generator from direct-current mains, connecting a rheostat in addition to the regular field rheostat in series with the field. Connect the negative terminal of a suitable voltmeter to the negative brush of the generator and the positive terminal to the pilot brush. The proper connections are shown in the following diagram.

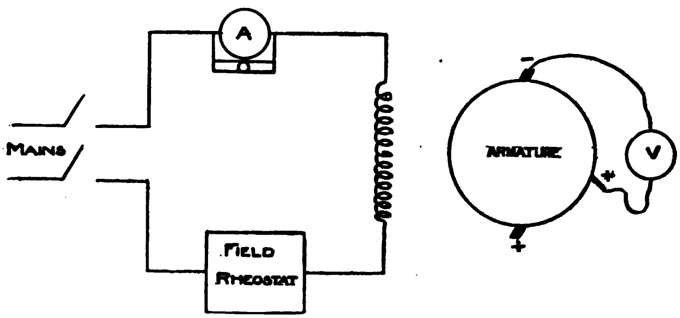


Fig. 18

Do not open the generator field without first putting in all the resistance.

Set the generator field rheostat for maximum resistance; then close the motor switch and start it slowly by means of its starting box. See that the voltmeter reads in the right direction. If it reads backwards, shut down the generator and connect the negative terminal of the voltmeter to the other brush of the generator. Adjust the speed of the generator by means of the rheostat in the field of the motor. Change the motor field resistance slowly. An increase in resistance will increase the speed, a decrease will produce the reverse effect. Record the speed. Move the pilot brush until the position which gives the maximum voltmeter reading is found, then adjust the field of the generator until the voltmeter indicates the rated voltage of the generator. Read the field current. If the voltage fluctuates, it is due to a jumping of the pilot brush. A slight pressure on the pilot brush with a pencil or fountain pen will stop the fluctuation.

Move the pilot brush until a position is found where the voltmeter reads zero. The pilot brush and the generator brush to which the voltmeter is attached should now be nearly side by side. Read the graduated scale giving the position of the pilot brush. This will be the zero reading, i.e., the reading from which the position of the pilot brush is to be reckoned. Now move the pilot brush in the direction of rotation of the armature taking readings of the voltmeter for every movement of the brush of ten electrical degrees. Proceed in this way until the brush has been moved completely around the commutator, then shut down and connect the load provided to the generator armature.

Diagram of Load Connections:—

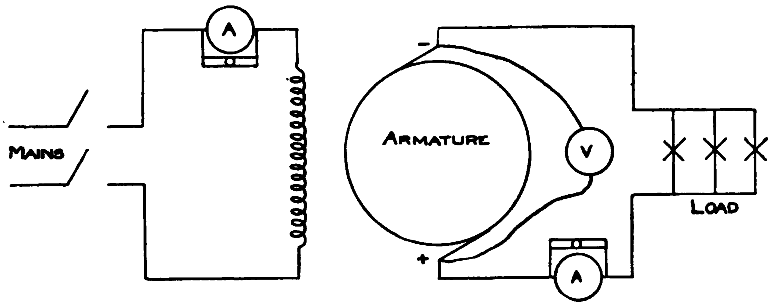


Fig. 19

An ammeter should be placed in circuit. This is to be arranged with a short-circuit block as shown in the diagram at A. Start the motor as before, then gradually throw on the load. If any sparking occurs the brushes should be adjusted. When the load is all on, adjust the speed of the generator. See that the field current is the same as in the no-load run, then take readings as before for every ten-degree position of the pilot brush. This completes the test.

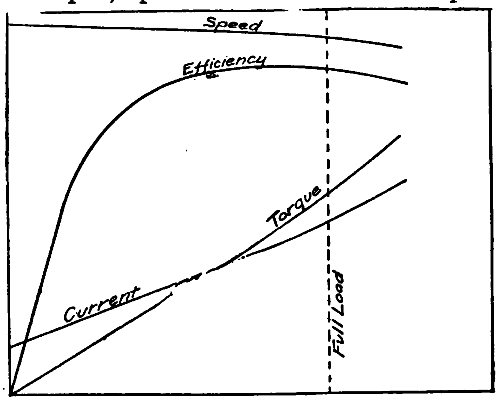
The results are to be plotted as shown on the second plot, with

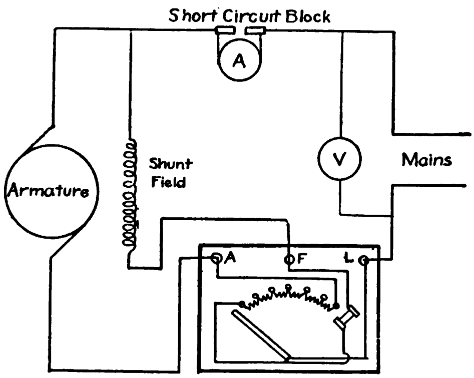
volts as ordinates and positions of the pilot brush in degrees measured from the negative brush as abscissae.*

If the potential about the commutator of a shunt motor is to be measured, the procedure will be essentially the same as that given for a generator. The only material difference will be that the motor will be operated as a shunt motor and no adjustment of its field will be necessary. The load may be applied in any convenient way.

IV
SHUNT MOTOR

The curves which are important for showing the operating characteristics of any shunt motor, are indicated in Fig. 20. In order to obtain these curves it is necessary to measure the electrical input, speed and mechanical output of the motor under different loads. The simplest way of determining the mechanical output is by means of one of the many forms of friction brake. This is the method to be adopted in this experiment. Connect the motor as shown in Fig. 21.





Figs. 20 and 21

The starting box shown in Fig. 21 is one with a no-field release, i. e., one in which the failure of the field current releases the arm on the starting box and shuts down the motor. It is possible that a starting box with a no-voltage release may be used instead. In this case the connections for the starting box will be slightly different. Before connecting up the motor make sure which type of starting box is used and connect accordingly.

After connecting the motor see that the ammeter is short-circuited, then close the main switch and bring the motor up to speed. The motor should be started under no load. Be sure that it rotates in the proper

*The absisae will be the observed reading of the voltmeter, minus the zero reading mentioned on page 21.

direction. If it starts in the wrong direction open the main switch and reverse the connections of either the armature or the field.

Never stop a motor, even if it has not attained full speed, by allowing the arm on the starting box to return to the starting position. The arm must not be allowed to return to this position until after the main switch is open. The failure to observe this rule always results in burning and finally in the destruction of the contacts on the starting box.

The approximate value of the full load current of any motor may be found by dividing its rated output by the voltage and the assumed efficiency at full load. A table giving the efficiencies which may be expected for machines of various sizes is given on page 16.

After the motor is up to speed, load it until it takes about 25% more than its full load current. Allow the motor to take run at this load for at least ten minutes in order to warm up, then several sets of readings of line current, line voltage, speed, balance, and weights if any are used in connection with the brake.

The speed will be obtained by observing the number of revolutions made by the motor in a minute. Be sure that the balance arm is kept in a horizontal position, and also that water is kept in the brake drum. This water will evaporate quite rapidly and will have to be occasionally replenished. Care should be taken not to wet the friction band about the brake drum.

After completing the readings for about 25% overload, reduce the load slightly and take another set. Continue in this way until no load is reached. then shut down the motor. About eight sets of readings should be taken at different outputs between 25% overload and no load. At the end of the run determine the zero reading of the brake.

In order to find the distribution of losses in the motor it will be necessary to measure its armature and field resistances. These resistances will be found by the fall of potential method applying Ohm's Law.

Disconnect the motor; then connect the armature in series with an ammeter and a considerable resistance to the mains. In determining the size of this series resistance the resistance of the armature may be neglected.

If a current of I is desired and the voltage of the circuit is E, the necessary resistance will be

$$\frac{E}{I} = R \text{ ohms}$$

In small motors of a few horse-power I may be 50 to 100 per cent. of full load current but in large motors a smaller current usually has to be used.

Note :—Be sure that the rheostat used in measuring the armature resistance has not only sufficient resistance but also has ample current-carrying capacity. A starting box can never be used used on account of this latter requirement. Measure the

current through the armature and the voltage drop across its terminals, with the armature in several different positions.

Since the armature resistance is small a voltmeter having a low-range scale will be necessary. Before, using this low-range scale be sure to try the voltage on the high range scale, in order to prevent injury to the instrument. As soon as a reading has been taken disconnect from the low voltage scale.

The resistance of the shunt field may be determined in the same way except that no series resistances will be required and the low voltage scale on the voltmeter will not be necessary. A lower range ammeter, however, will be required.

Precaution:—When measuring the field resistance be sure to disconnect the voltmeter before breaking the circuit. Failure to do this will result in serious damage to the voltmeter from the field discharge. In large machines precautions have to be taken when the field circuit is broken to prevent injury to the field itself.

Calculations.

$$\text{Output in h. p.} = \frac{2\Pi n\, T}{33000}$$

where n is the rev. per min. made by the motor and T is the torque computed from the brake reading.

$$\text{Efficiency in per cent.} = \frac{\text{h. p. output} \times 746}{\text{I E}} \times 100$$

where I and E are the measured line current and line voltage respectively.

The total watts lost in the machine are $W_t = \text{Input} - \text{Output}$. The loss in the field is $I_f{}^2 R_f$. Since the field current is found by dividing the voltage E by the field resistance the field loss becomes

$$I_f^2 R_f = \frac{E^2}{R^2_f} R_f = \frac{E^2}{R_f} = W_f$$

The armature current cannot be found by dividing the terminal voltage by the armature resistance since the armature exerts a back e. m. f. which opposes the flow of the current.

The armature current, I_a, may be found by subtracting the field current from the line current.

$$I_a^2 R_a = (\text{I line} - I_f)^2 R_a = W_a$$

$W_t - (W_a + W_f)$ gives the remaining losses i. e., friction and windage and core losses or what is known as stray power.

Calculate the distribution of the losses at full load in per cent of input and plot a complete set of motor curves.

Before leaving the laboratory make a sketch of the connections and the form of brake employed, also see that the numbers of the instruments used are recorded as well as the units in which they are read at the head of the columns of data. All zero errors of instruments must be recorded in order that proper corrections can be applied to the data.

V
SERIES MOTOR

(Before reading these notes read those on the SHUNT MOTOR.)

This test is to obtain the characteristic curves of a series motor and is to cover the same ground as the test on the shunt motor.

The shunt motor is essentially a constant speed motor and is generally used for driving stationary apparatus where good speed regulation is required and where the motor does not have to start under any great load. When subjected to heavy load at starting a series motor is far superior to a shunt motor. A series motor is particularly adapted to work requiring good effort under widely varying speeds and loads. It is for this reason that series motors are universally used for traction purposes, electric hoists and the like.

If a shunt motor were used for electric traction, it would require large current at starting, as well as on grades where it would tend to maintain the same speed as on a level. The series motor, on the other hand, exerts good torque at starting without excessive current, and on grades slows down and does its work at a moderate speed and current. This particular property of a series motor is due to its field being connected in series with the armature.

The speed of a motor is inversely proportional to its field strength and nearly proportional to the voltage at the terminals of its armature. The torque or turning moment exerted by the armature is proportional to the product of the field strength and the armature current.

Since the field and armature of a series motor carry the same current, when this current is large, as in starting or on grades, the torque will be large and the speed low. As the motor speeds up, the increase in back e. m. f. will decrease the current and cause the field to weaken. Therefore the speed of a series motor increases rapidly with decrease in load. Due to this increase in speed, sufficient load must always be maintained to prevent dangerously high speed or racing. Fuses are no protection since the excessive speed occurs under light load and small current.

The current in the armature of a shunt motor or in a series motor is equal to the difference between the impressed voltage and the back e. m. f. generated by the armature, divided by the resistance. This resistance is the armature resistance in the case of the shunt motor and the combined resistance of the armature and the field in the case of the series motor. If, therefore, full potential is applied to a motor before it speeds up and generates a back e. m. f. an excessive current will flow which will probably cause serious damage. It is to prevent this excessive current that a starting box is used. Although the function of a starting box is the same whether it be used in connection with a series or shunt motor, its arrangement may be somewhat different. The little

magnet which holds the movable arm in the running position on a starting box for a shunt motor must be either in series with the field or connected through resistance across the mains. For a series motor this magnet must be either in the main circuit, or shunted across the mains as in the case of a shunt motor.

A series motor must always be started under sufficient load to prevent racing, but on the contrary a shunt motor should be started under no load or as little load as possible.

Test.—The motor used in this experiment is provided with a circuit breaker which opens the circuit in case the current falls below a safe minimum. An overload circuit breaker is also provided.

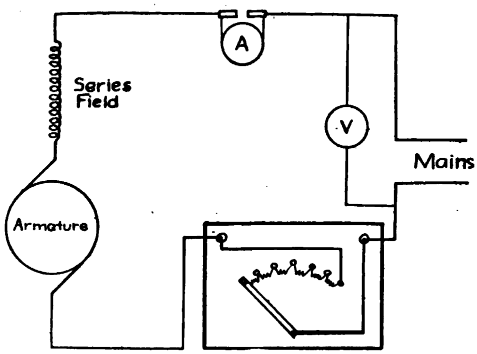


Fig. 22.

Inspect the motor assigned and notice the type of brake used for getting the output and also the kind of starting box employed.

Connect up the motor as shown in Fig. 22.

Note:—In case a starting box has its little magnet across the line instead of in the main circuit, another connection to the starting box will be needed.

First close the under load and over load circuit breakers, then close the main switch and with a small load on the motor bring it slowly up to speed. The under load circuit breaker will have to be held until the main switch is closed. Keep the ammeter well short-circuited while starting.

Put about twenty-five per cent overload on the motor and allow it to run ten or fifteen minutes; then proceed according to the directions given under the shunt motor. The load, however, in the case of the series motor should not, of course, be reduced to zero. Ask what is the safe maximum speed for the motor used and let the minimum load be determined by this speed.

At the end of the run shut down and measure the resistance of the armature and field separately, and from the values found calculate the percentage distribution of losses at full load.☆

Watts lost in armature $= I^2$ (full load) R_a.

Watts lost in field $= I^2$ (full load) R_f.

Watts lost in stray power is to equal the total losses minus the above I^2R losses.

☆ *Since the resistances of both the armature and the field of a series motor are low, a considerable resistance must be placed in*

series with each when measuring its resistance. Before measuring these resistances read the directions for measuring armature resistance under the Shunt Motor. Be sure to disconnect the voltmeter before breaking the circuit.

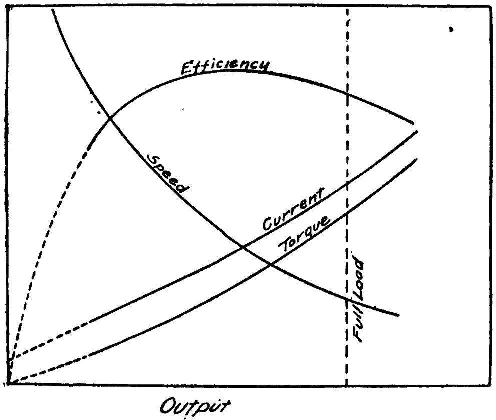


Fig. 23.

Record the necessary dimensions of the brake and its zero reading as well as the numbers and zero readings of all the instruments used in the test.

The curves indicated in Fig. 23 are to be plotted, the percentage distribution of losses is to be calculated, and all the important results are to be tabulated.

VI

COMPOUND MOTOR.

Cumulatively - Compounded Motor. — There are certain classes of work which require motors that will develop good torque at starting and which will operate with only moderate changes of speed under ordinary variations of load.

An ideal motor for this purpose would combine the starting qualities of a series motor with the running properties of a shunt motor. Such a machine is obviously impossible, but something approaching it may be obtained by putting a compound winding on the field of a shunt motor and connecting this compound winding in series with the armature in such a way that it assists the shunt coils. A motor arranged in this way will develop a fair torque while starting, due to the increase in the strength of its field produced by the heavy starting current in the series winding. When once up to speed the effect of the series coil will be small and the speed regulation will be fairly good. The speed regulation, however, cannot be nearly so good as that of the shunt motor, neither can the starting torque be so good as that of the series motor. The good qualities of each type of motor must be sacrificed to a very considerable degree in order that the motor, to a limited extent, may possess the qualities of both.

A motor with a compound winding connected so as to aid its shunt field is called a cumulative motor. Such motors are largely used for elevators.

Differentially-Compounded Motor.—The speed regulation of a shunt motor is sufficiently good for most purposes, but in certain cases as, for example, in textile mills where a slight variation in speed may affect the work a differentially-compounded motor may be used.

A properly designed differentially-compounded motor will run at nearly constant speed from no load to full load.

The speed of a shunt motor falls off slightly with increasing load but may be maintained constant by weakening its field as the load comes on. This may be accomplished manually by slightly increasing the resistance of a rheostat placed in the shunt field, but may be done automatically by differentially compounding the motor.

If, in addition to the shunt winding, a few turns of heavy wire are wound on the field, and these turns are connected in series with the armature, any change in the current in the armature will affect the field and consequently the speed of the motor. If these turns are connected so as to act in opposition to the shunt field winding, any increase in the load on the motor will weaken the field and increase the speed over that which the motor would have if the shunt coils alone were used. If the number of turns is properly adjusted the speed will remain practically constant from no load to full load. If too many series turns are used the speed will rise; if too few the speed will fall. In order to adjust the effect of the series field, a shunt is often provided by means of which the current through the series turns may be varied. If a shunt is used it is usually adjusted by the manufacturer before the motor leaves the shop.

Since the weakening of the field by the series coils may be considerable when the motor is started or is heavily overloaded, care must be taken in handling a motor of this type. A differentially-compounded motor should always be started slowly and should be well protected from heavy overloads.

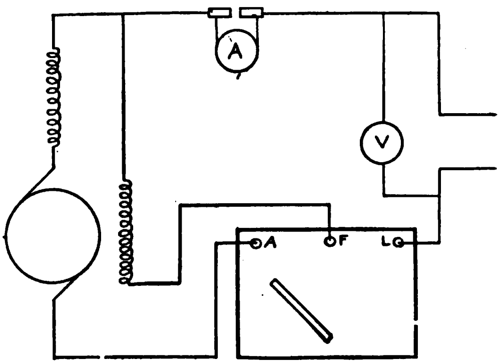


Fig. 24

Test. — Inspect the motor assigned for this experiment and from its name-plate rating determine what instruments will be required.

Note the form of brake and starting box used, then connect up as shown in Fig. 24.

Take readings for motor curves, following the directions given in the tests of the shunt and the series motors.

Data for three sets of curves should be taken, the first set with the series coils out; the second, with the series coils connected cumulatively; and the third, with the series coils connected differentially and shunted in case a shunt is provided. The series coils should not be shunted during the cumulative run.

If time permits take data for computing the percentage distribution of losses at full load.

VII

COMMUTATING POLE MOTOR

The speed of any shunt motor is given by

$$S = \frac{PD - I_a R_a}{K\phi_a}$$

Where PD is the impressed voltage, I_a and R_a the armature current and armature resistance respectively, and ϕ_a the armature flux. K is a constant depending upon the armature winding.

The speed may be varied, as may readily be seen from the formula, by changing either R_a or ϕ_a. Changing R_a results in very poor economy. If the speed is reduced to half by increasing R_a, approximately fifty per cent of the power supplied to the motor will be wasted in this resistance.

The variation of speed which can be obtained by altering ϕ_a is limited in the ordinary shunt motor to about twenty-five per cent on account of the sparking which occurs when a motor is run with a weak field. This sparking is caused by the field distortion produced by the armature reaction acting on a weak field, making it impossible to maintain the proper flux at the point of commutation to neutralize the effect of the self-induction in the short-circuited armature coils.

This difficulty is overcome in shunt motors of the inter-pole type by putting small magnetic poles midway between the regular poles. These auxiliary poles are connected in series with the armature so as to oppose the field due to armature reaction and maintain the field necessary for commutation. Since these auxiliary poles are in series with the armature, their strength will vary with the armature current. Consequently the field for commutation varies in proportion to the current load on the motor. Motors of this type, if properly designed, will develop their rated output over a very considerable range of speed, will carry overload and will run in either direction sparklessly without any change in brush position.

The controller for a motor of the inter-pole type is usually a combination of an ordinary starting box and a field rheostat. The first few notches on the controller correspond to a starting box and are not running positions. A movement of the controller handle beyond the first running position inserts resistance in the field

circuit weakening the field and causing the motor to speed up. The controller may also be so arranged that the direction of rotation of the motor can be reversed.

The test on the motor used in this experiment is to obtain curves similar to those called for under the Shunt Motor. Two sets of readings are to be taken, one with the controller set for minimum speed, and one with the controller set for maximum speed. Take data at slow speed, allowing the motor to run at least ten minutes at full load before recording any data.

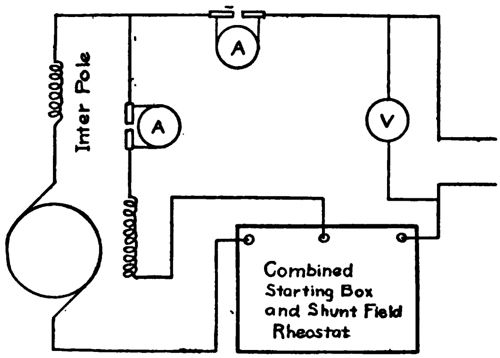


Fig. 25

The connections for the test are shown in Fig. 25. In making these connections the inter-poles must be connected in such a way that the field produced by them opposes that caused by armature reaction. To test whether the inter-poles are connected properly, start the motor and bring it up to full speed, i. e., the highest speed at which it is designed to run, then apply full load. If sparking occurs shut down and reverse the inter-pole connections.

Note:—The controller may or may not open the main circuit. If it does not, a main switch, not shown in the diagram of connections, must be used. Instead of measuring the field resistance which should include that resistance in the controller which is in series with the field an ammeter should be put in the field circuit during the run to indicate the field current. The reading of this ammeter multiplied by the line potential will give the I^2R loss in the field circuit. This I^2R loss will be very different at different speeds.

At the end of the test measure the armature resistance and the resistance of the series winding on the inter-poles. Both the armature resistance and the resistance of the series field will be low so that a rheostat must be put in series with them when measuring their resistance.

Results required:—Two plots on separate sheets giving curves of speed and output, current and output, efficency and output, and torque and output. One set of curves should be for the run with the controller handle in the position for minimum speed; the other set for that with the controller handle in the position for maximum speed.

Calculate the percentage distribution of losses at full load at both speeds.

The speed should be measured by means of the voltage generated by a magneto attached to the motor shaft or by some form of direct reading tachometer. The magneto with its voltmeter, or tachometer if used, must be calibrated at the beginning of the test over the range of speed at which the motor is to be operated.

VIII

EFFICIENCY BY THE STRAY POWER METHOD

The general expression for the efficiency of any apparatus is the ratio of its output to its input. Since the difference between the input and the output must be equal to the sum of the losses, the equation may be written

$$N = \frac{\text{Output}}{\text{Output} + \Sigma \text{ losses}} \quad (1) \text{ or } N = \frac{\text{Input} - \Sigma \text{ losses}}{\text{Input}} \quad (2)$$

The calculation of efficiency by the measurement of the losses, has distinct advantages in both accuracy and ease of manipulation. If the total losses are 10% of the input, and an error of 5% be made in their determination, the error introduced into the efficiency will be of the order of 0.5% whereas an error of 5% in the determination of either input or output by direct measurement, will cause nearly 5% error in the efficiency. By the use of formulae (1) and (2) for a generator and motor respectively, all terms may be expressed in electrical units. The power saved by this method is also an important consideration.

The total losses of a generator or motor may be divided as follows:

Copper losses: (a) in the field; (b) in the armature.

Iron losses: (a) Hysteresis losses in the field poles and in the armature iron.

(b) Eddy current losses in the field poles and in the armature iron.

Mechanical losses: (a) Bearing and brush friction.
(b) Windage.

The sum of the iron losses and the mechanical losses are called the "stray power" losses, and while the components are capable of separate determination only with considerable labor, their sum is very easily found.

Method of finding the stray power:—Since the iron losses depend upon the speed and the armature flux, and the mechanical losses depend upon the speed, the stray power will vary somewhat with the load. Therefore, to measure the stray power accurately we must reproduce the proper speed and armature flux for the load desired. The full-load speed is given on the name plate, and,

although the flux cannot readily be directly measured, we may make use of the induced armature voltage, $E_a = k\phi S$. See equation p. 29. Since at a given speed, E_a is proportional to the armature flux. But as $E_a = V_t - I_a R_a$ (3) for a motor and $E_a = V_t + I_a R_a$ (4) for a generator we may calculate the proper E_a for the conditions desired.*

If we run a machine at no load *as a motor* with the proper speed and induced armature voltage, the total input, $V_1 I_0$, is equal to the total losses present. These losses are 1st. the copper losses in the field and the field rheostat, 2nd. the losses in the rheostat in the armature circuit, and 3rd. the total losses in the armature; or,

$$V_1 I_0 = V_1 I_f + I_a{}^2 R_1 + V_t I_a \quad (5)$$

Where V_1 = line voltage; I_0 = total current supplied; I_f and I_a = field current and armature current respectively; R_1= resistance of rheostat in armature circuit; V_t = voltage measured at terminals of the armature, which is equal to V_1 only when there is no rheostat between the armature and the line.

The last term alone we need for computing the stray power, since all the mechanical + iron losses are supplied by the energy given to the armature circuit. Therefore the armature input less the armature copper loss equals the S. P. or,

$$\text{S. P.} = V_t I_a - I_a{}^2 R_a \quad (6)$$

where R_a is the mean resistance of the armature circuit.

An approximate value of the stray power, correct to within 2-3%, may be obtained by running the machine at no load at the proper speed with normal voltage impressed across the armature terminals. The method of calculation will be the same as that given above. The approximate method is not to be used in this test.

To calculate the efficiency of the shunt generator from the data obtained use equation (1), which may be expressed as follows:

$$\frac{V_1 I_1}{V_1 I_1 + (I_1 + I_f)^2 R_a + V_1 I_f + \text{S. P.}}$$

where the symbols have the same meaning as in equations (5) and (6), and I_1 = total current for the load under consideration. The 2nd. and 3rd. terms of the denominator are the armature and field copper losses respectively, whose values are readily found when I_f is known. Since I_f is the field current necessary to produce the full-load flux at no load and therefore with negligible armature reaction, the field current necessary to produce the same armature flux when the full-load armature reaction is present must be greater. In the absence of definite information assume the increase for full

* V_t = the voltage at the armature terminals, and I_a and R_a are the armature current and armature resistance respectively.

load current to be 5%. All terms now being known, the equation may be solved.

The motor equation will be

$$\frac{V_1 I_1 - (I_1 - I_f)^2 R_a - V_1 I_f - S.\ P.}{V_1\ I_1}$$

Make the same allowance for the effect of armature reaction on the field current, I_f, as in the generator calculation.

TEST

Object:—Calculation of the full-load efficiency of the machine assigned.

Apparatus:—A d-c. motor or generator with suitable rheostats for armature and field circuits, starting box, tachometer or magneto, and the necessary meters for the electrical measurements.

Test:—Measure the armature resistance of machine to be tested (See Fig. 12.) Calculate by equation (3) or (4) the proper induced armature voltage and the proper armature terminal voltage for full load. For this calculation it will be sufficiently accurate to assume the full-load armature current equal to the total current at full load. Use the name plata data for determining the proper speed.

Connect the machine as a motor to mains of proper voltage (See Fig. 27). Note that R_2 changes the excitation of the field (changes both flux and speed) and that R_1 changes the armature terminal voltage (changes the speed only). Cut out all the resistance in R_1 and R_2 and bring the motor up to speed. Calibrate the speedometer at two or three points near the speed desired and find the average constant of the speedometer. Reproduce the desired V_t and speed by adjusting R_1 and R_2. When the proper setting is obtained read all instruments. Record three or four sets of readings. Stop the motor and disconnect all temporary wiring.

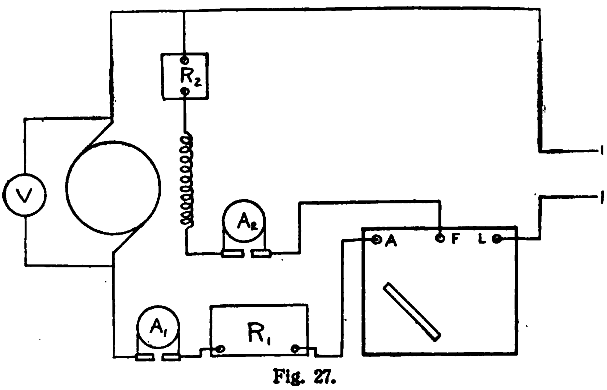


Fig. 27.

Precaution:—In measuring armature resistance use a current at least one-half of the full-load value if possible, since the brush-contact resistance varies markedly at low current densities.

In obtaining the proper speed and voltage it will be more convenient to adjust V_t first. Be sure that the rheostats used are of the proper resistance and current-carrying capacity.

Calculate the full-load efficiency from the data obtained.

IX

D. C. COMPOUND GENERATOR

This experiment is to determine the external shunt and compound characteristics and magnetization curve of a compound generator. The machine used in this test may be motor or engine driven. In either case the speed of the generator will vary slightly with the load.

If for any reason a generator is to run at speed which differs from the rating, its voltage should be changed to correspond with the speed. In order to maintain the flux conditions for which the machine was designed, the change in speed should be proportional to the change in voltage. If the ratio of speed to voltage is not kept constant, not only will the flux be changed but the percentage compounding will also be altered. A decrease in voltage produced by a decrease in field excitation will always result in an increase in the compounding and an increase in the tendency to spark under load.

Since the limiting value of current for any machine is determined by the I^2R loss in the conductors, the current rating of a machine cannot be increased as the voltage is reduced in order to keep the kw. rating constant. The current rating of a machine is not affected by any ordinary change in voltage.

Test. Shunt Characteristic.—Connect the generator as shown in Fig. 28, being sure to have the series coils cut out. Short-circuiting the series coils will not be sufficient since they are of very low resistance.

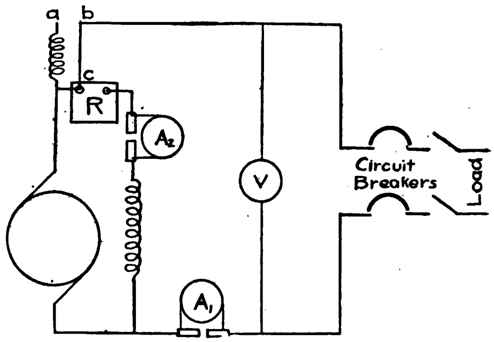


Fig. 28

Put all the resistance in the shunt field rheostat, R, and see that the brushes are at the neutral point, then bring the machine up to speed. If it fails to build up and come up to voltage, one of the several things mentioned under Generator Connections may be the trouble.

Before trying to locate the fault be sure that there is not an open circuit in the field connections, and also that resistance in the field rheostat has been cut out. A shunt machine will not excite if it has more than a certain critical resistance in its field circuit.

The absence of a very small deflection of the voltmeter needle will indicate lack of residual magnetism. In this case current must

be put through the shunt field coils from an exteral source of power in order to restore the magnetism.

If on closing the field circuit, the small deflection of the voltmeter which is due to residual magnetism decreases, the shunt field connection is reversed.

After having built the machine up, make a preliminary run to determine the best position for the brushes. Do not alter the brushes without first speaking to an instructor.

With no load on the generator adjust its terminal voltage by means of the field rheostat to the proper value for the speed at which the machine is to be run. Read the speed, terminal voltage, field current and line current. The latter will be zero. Increase the load and take another set of readings. Proceed in this way until either the rated current is reached or the voltage has dropped so that no further increase in load is possible,* then reduce the load current to zero taking readings.

About ten to twelve sets of readings should be taken from no load to full load and an equal number should be taken on the return to no load.

Put all the resistance in the field circuit. If a switch is provided for the field open this, but *not until all the resistance in the field rheostat is in series with the field.* If the generator is motor-driven shut down the motor.

Compound Characteristics.—Connect in the series field so that it assists the shunt coil. A rapid fall of voltage when the load is applied will indicate that the series field connections are wrong. The connections are the same as in Fig. 28 except that the points a and b are connected and the connection between b and c is removed.

When the connections have been properly made, take the compound characteristics going from zero to full load then back to no load.

Magnetization Curve.—The magnetization curve of a generator or motor shows the relation at constant speed between the no-load terminal voltage and the exciting current. The magnetization curve is often called an open circuit curve or saturation curve.

Since the ampere-turns in the field are proportional to the field current and the no-load terminal voltage is proportional to the armature flux, provided the generator or motor be driven at a constant speed, the magnetization curve really gives the relation between ampere-turns in the field and armature flux. Since speed is an element in determining the voltage, the speed at which a magnetization curve is taken should always be stated. In general this should be the rated speed of the machine.

* Some compound generators will not deliver full-load current without their series coils.

Reduce the excitation of the generator. Then disconnect the field from the armature and separately excite it from some external source having a voltage about equal to the normal voltage of the generator. A large resistance equal to at least ten times the resistance of the shunt field coils should be inserted in addition to the regular field rheostat. This extra resistance must be capable of large variation and at the same time be able to carry the field current without overheating. Such a resistance is not often at hand. Several rheostats of different resistance and current capacities will answer as well, provided care is taken to cut out the rheostats with the highest resistance and smallest current capacity first. The proper connections are shown in Fig. 29. R¹ being an extra rheostat.

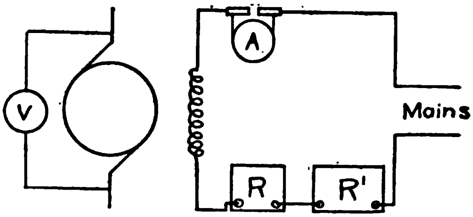


Fig. 29.

Bring the generator up to speed if it has been shut down, and take readings increasing the field current from zero to a maximum and then back to zero. In obtaining data for the rising portion of the curve, care must be taken not to increase the current by more than the desired amount and then reduce it. Such procedure will introduce loops in the curve and render it of no value. During the descending portion of the curve a similar precaution is necessary.

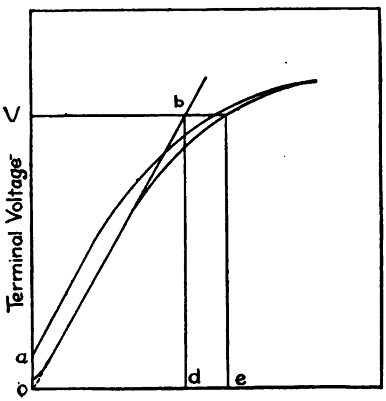


Fig. 30.

A complete magnetization curve is shown in Fig. 30.

Magnetization curves are useful in comparing different types of machines. Due to the effect of residual magnetism, a magnetization curve will usually start at a point slightly above zero voltage. Should the residual magnetism be absent, the curve will start at zero.

For low values of the field current, the reluctance of the iron circuit, i. e., its resistance to the passage of magnetic lines of force, is small and nearly the entire field current is necessary to force the flux through the air-gap, which has very high magnetic reluctance as compared with the iron. The reluctance of the air-gap is constant, hence the portion of the field current necessary to force any flux through it will be proportional to the flux. If then a line be drawn tangent to the lower part of a magnetization curve, it will

show for each degree of magnetization how much field current is necessary to force the flux through the air gap.

For example:—o b in Fig. 30 is such a line. For condition represented by the voltage V, a field current equal to *o e* is necessary to force the flux through the whole machine. The portion *o d* is required for the air-gap, *d e*, for the iron.

From the data obtained in this experiment plot the shunt and compound characteristics and the magnetization curve. All characteristics should have the corresponding speed curves plotted with them. On the magnetization curve draw a line showing the field current required to force the flux through the air gap and find the percentage of field current required for the air gap at rated voltage.

X

HEAT RUN

The limit of output of any piece of electrical apparatus is determined very largely by its heating under load. Consequently a heat run under rated conditions is an extremely important part of any acceptance test. A motor or generator may be perfectly satisfactory in so far as efficiency, regulation, etc., are concerned, but may be absolutely incapable of standing continuous service at the load for which it is designed on account of the excessive temperatures reached by its parts. If the temperature of a motor or other piece of electrical apparatus becomes excessive, its insulation will very rapidly deteriorate and finally break down.

In the Standardization Rules of the American Institute of Electrical Engineers, the following values for the maximum temperature rise under rated conditions of load are recommended.

Field and armature circuits by resistance measurements	50° C.
Commutator and brushes by thermometer	55° C.
Bearings and other parts by thermometer	40° C.

These temperature rises are referred to a room temperature of 25° C. If the room temperature during test differs from 25° C., corrections should be applied to the actual measured temperature rises to reduce them to the temperature which would have been obtained had the room temperature been standard.

The rise in temperature should be measured, except in the cases noted below, after a run of suffiicient duration to insure practically constant temperature having been reached.

Certain classes of motors, notably railway motors and series motors designed for intermittent service are rated on a full load

duty for some specified time as an hour or half hour. The increase in temperature of the different parts of motors of this type at the end of a full-load run for the specified time should not exceed the values already given.

It is impossible to make a satisfactory full-load heat run in a laboratory period of two or three hours, unless either a very small machine or one designed for intermittent service be used:

Test:—The machine used for this experiment will be either a small shunt motor or a series motor rated on a half hour duty. The load will be obtained either by a friction brake or by driving another machine which can be loaded as a generator.

The proper connection for a heat run on a shunt motor and series motor are given in Figs. 31 and 32 respectively. R is a rheostat for keeping voltage at its rated value.

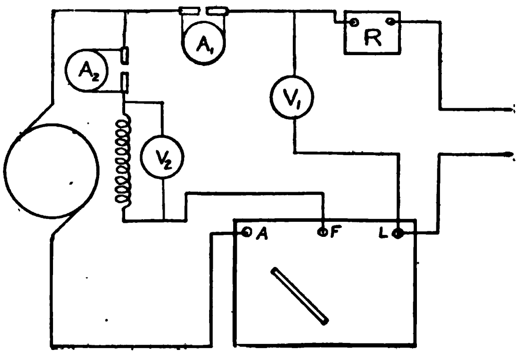


Fig. 31.

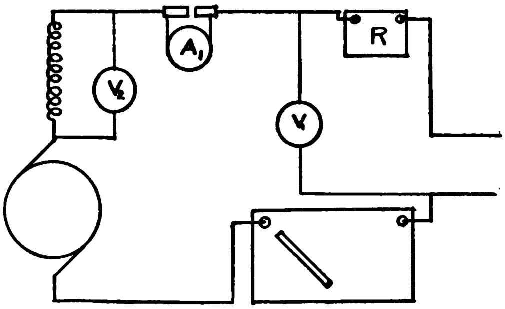


Fig. 32.

If a generator is to be used for load, it must be capable of absorbing without overload the power output of the motor under test.

The proper conections for the generator are shown in Fig. 28 although voltmeter V, ammeter A_2 and circuit breakers may be omitted.

Ammeter A_1 is to guard against overload.

Measure the resistance of the field and the armature circuits, taking readings quickly to avoid any appreciable heating. Also record the tĕmperature of the room near the machine and the temperature of the machine by thermometer.

The armature resistance must be measured with the armature in a definite position which may be marked and used for the hot resistance measurement at the end of the test. *The resistance must not include the brush resistance.*

Note:—The resistance of a series field is always very low. A suitable rheostat must therefore be put in series with a series field when measuring its resistance.

Having measured the resistances make the proper electrical

connections for the heat run. See that there is oil in the bearings and that the brushes are properly set, then bring the machine up to speed and quickly apply load until the motor takes its rated current. If the rated voltage of the motor is less than the voltage of the mains from which it is to be run a small variable rheostat should be inserted in one main in order to reduce the voltage to the proper value. Record the time at which the motor is started and as soon as possible after starting, record the readings of all instruments as well as the speed of the motor and the room temperature.

Note:—A magneto may be convenient to use for measuring speed.

Hold the rated conditions of load constant during the entire heat run taking readings of speed, room temperature and all instruments at regular intervals. If it is possible to place thermometers on the field coils where they will not be broken, the reading of these thermometers should also be recorded.

The interval between readings should be short, from three to five minutes at the beginning of the run, but may be increased somewhat after the first half hour.

If a shunt motor is tested, the heat run should be continued until the motor reaches constant temperature. If time will not permit of this, the run should should be continued as long as possible, at least for an hour and a half.

If the machine tested has a half hour rating, the heat run should be continued only for this length of time.

At the completion of the heat run, stop the motor and measure the resistance of its armature and field as quickly as possible.

Note:—Be sure that the hot and cold armature resistance measurements are made with the armature in exactly the same position.

As soon as the machine has been shut down, place a thermometer on its commutator and others on its field and bearings. These thermometers should be properly protected from radiation. See page 3.

From the value of the field resistance obtained during the run, calculate and plot a curve of the temperature rise in the field. See page 2. Calculate the final temperature rise in the armature.

In addition to plotting a curve of temperature rise in the field a curve should be plotted showing the change of speed due to heating. Both curves should be plotted against time as abscissae.

The final temperature rise in the armature should be calculated as well as the percentage change in speed caused by heating.

Tabulate results giving average line current, average line voltage, final temperature rise in the armature and in the field, the temperatures by thermometers, and the percentage change in speed due to heating.

XI

PARALLEL OPERATION OF SHUNT GENERATORS

In order that two or more generators may be operated successfully in parallel, their characteristic curves must be such that the machine will divide the load in proportion to their rated outputs and at the same time be in stable equilibrium.

The shape of the characteristic curves of shunt machines insures the second of these conditions. Any two or more shunt generators may be run in parallel in so far as stability is concerned, but whether or not they divide the load properly will depend upon the relative slopes of their characteristics.

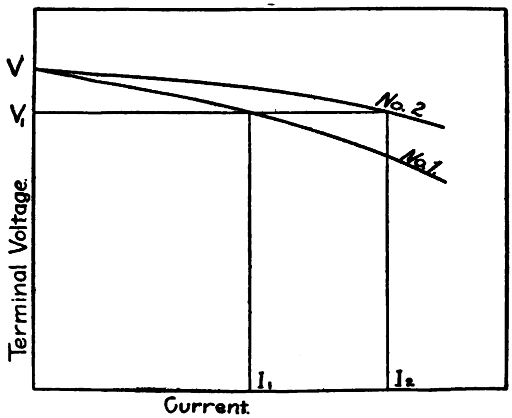


Fig. 33

Any two machines when in parallel must have the same terminal voltage since their terminals are connected to the same bus-bars.

Suppose two dissimilar shunt generators are brought to the same potential and are then put in parallel. Let the load be zero. Fig. 33 will represent the characteristics of two such machines.

The potential of both machines is the same and the current in each is zero. Let a load now be thrown in circuit. The terminal potential of both machines will decrease but must still be the same. If the machines are loaded until the potential has fallen to V_1, the current in machine No. 1 will be I_1; that in No. 2, I_2. The current in No. 2 increases faster than the current in machine No. 1, and if the machines were of the same size, No. 2 would be overloaded before No. 1 reached full load. It is obvious that the characteristics of the two machines must be the same if they are to share the load equally at all loads. If the machines are of different sizes their characteristics should be similar, that is, their characteristics should each show the same drop in voltage for the same fractional part of full load current.

There is no great objection to operating in parallel shunt generators with slightly different characteristics, since the only effect will be a disproportionate division of load. This will cause no trouble so long as neither machine is overloaded. Moreover, if necessary, the load may be divided properly at any output by adjusting the field rheostat.

The proper connections for the parallel operating of shunt generators are shown in Fig. 34.

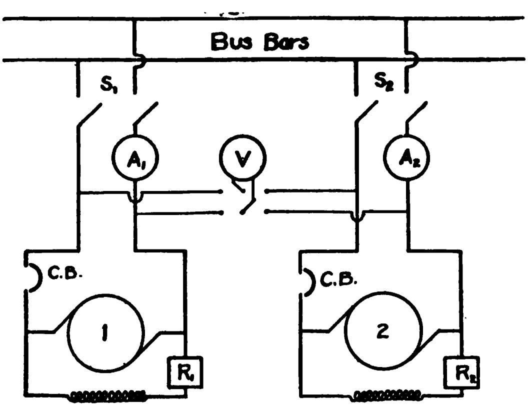


FIG. 34

CB represents the circuit breakers. A^1 and A^2 are ammeters. The voltmeter V should be arranged so that it may be connected to either machine or to the bus-bars.

Suppose machine No. 1 is running under load and it is desired to throw in machine No. 2. First bring machine No. 2 up to speed and adjust its field rheostat until the voltmeter V reads the same whether connected to the terminals of No. 2 or to the bus-bars. Be sure that the polarity of the incoming machine is the same as that of the bus-bars. If the switch S_2 is now closed, machine No. 2 will be parallel with machine No. 1. It should, however, take no load. It may be made to take its proper share of the load by slowly increasing its field and decreasing the field of the other machine to keep the bus-bar potential constant.

Note :—If the potential of No. 2 is high, it will take load when it is put in parallel with No. 1. If the potential is much too high, it may be considerably over loaded, and may even drive the other machine as a motor. If the potential is too low, there will be a rush of current from No. 1 which will drive No. 2 as a motor.

To take a generator out of service, its field should be slowly weakened until the current delivered by the machine becomes zero. At the same time it will be necessary to increase the field excitation of the other machine to maintain constant voltage at the bus-bars. When the current delivered has been reduced to zero, the generator should be disconnected from the bus-bars by tripping its circuit-breaker and then opening its main switch or if there are no circuit-breakers by simply opening the main switch.

Test.—Connect the generators for parallel operation as shown in Fig. 34 then make a preliminary run on each generator in order to find the best brush position for the operation of the machines from no load to full load. To determine this position, bring the voltage of one generator up to its rated value, having first put the brushes in the neutral plane. Give the brushes a slight forward lead, then slowly apply load, noticing any tendency to spark. If there is sparking at full load, increase the brush lead slightly, then remove load and see if the no load commutation is still good.

If there is sparking, the lead will have to be reduced. A few trials ought to be sufficient to adjust the brushes so as to have fairly good commutation over the entire range of load. In actual operation of generators, the position of the brushes would probably be changed to suit the load instead of being kept fixed as will be done in this experiment. If the neutral plane of a generator shifts much with load, the commutator and brushes will heat badly if the generator is run long at no load with full load brush setting or vice versa. This heating is due to the large current produced in the coils short circuited during commutation. Having adjusted the brushes of one machine, adjust the brushes of the other in the same way.*

Having the brushes on both of the generators properly set, take the shunt characteristics of each machine separately, starting each characteristic at no load at the rated voltage corrected to correspond to the actual speed at which the machines are driven.

NOTE:—If circuit breakers are provided, these must be closed before closing the switches. In case the circuit breakers open during the test, they must not be closed until the switches in the circuit which they protect have first been opened.

Put the generators in parallel at no load. Load the system slowly, recording the line currents, terminal voltage, and speeds for about seven or eight different loads up to full load. If the machines do not divide the load in proportion to their rated outputs, load them until either delivers its full-load current, then take off the load and disconnect the generators from the bus-bars by opening the switches S_1 and S_2.

Now close switch S_1 and bring machine No. 1 up to full load, keeping the voltage constant by adjusting the field rheostat. Make the voltage of machine No. 2 exactly the same as the voltage of machine No. 1, and close S_2. Generator No. 2 should take no load. Now increase its field and note the effect on both the current distribution and the voltage system.

Reduce the current taken by No. 2 to zero, and then note the effect of weakening the field of the generator which is loaded.

Again reduce the load of No. 2 to zero, then slowly increase its field and at the same time weaken the field of No. 1 so as to keep the potential of the system constant. Note the effect.

Care must be taken when changing the brush lead of machines in parallel as a small change in lead will often make considerable

* Never loosen the locking device on the yoke which carries the brushes until a firm hold has first been taken of the handle attached to the yoke. There may be a considerable drag produced on the yoke by the friction of the brushes on the commutator.

difference in the distribution of the load. A backward movement of the brushes of a generator in parallel with others will invariably make it increase its load.

From data obtained in this test, plot the shunt characteristics of each machine and a curve showing the ratio of current load taken by each machine when put in parallel with one another at no load and then loaded. All curves should be plotted on the same sheet with current outputs as abscissae.

A brief discussion of the action of the generators under test should be given in the report.

XII

PARALLEL OPERATION OF COMPOUND GENERATORS

Compound generators are used to maintain constant potential at some definite point as at the switchboard or some definite point on the line. For this reason, they are generally more or less over-compounded to compensate for the drop of potential between their terminals, and the point at which constant potential is to be maintained.

The operation of compound generators in parallel is similar in many respects to the parallel operation of shunt machines but in order to insure stability one additional condition must be fulfilled, for if, two or more compound generators are paralleled and one, for any reason whatsoever, takes more load, its potential will tend to rise due to the effect of its series coil. This will cause the machine to take still more current which in turn will still further increase its voltage. The result of this accumulative effect will be that the machine which first starts to take a little more load will almost instantly grab all the load and in addition will tend to run the other machines as differentially compounded motors.

This is, of course, not only fatal to parallel operation but also injurious to the machines unless they are properly protected by circuit breakers.

This unstable condition can be entirely prevented by paralleling the series coils as well as the machines themselves. Then, if any one machine attempts to increase its load, the increase in current divides between the series coils of all the generators inversely as the resistances of the coils. The result is that no one machine can increase its potential without also increasing the potential of the others and cannot, therefore, take load at the expense of the other generators.

The characteristics of two compound generators in parallel are shown in Fig. 35.

If the generators are loaded until their potential is V_1, the current in each will be the same, or I. If the load is increased generator No. 1 will increase its load more rapidly than generator No. 2. If the load is reduced the reverse will happen.

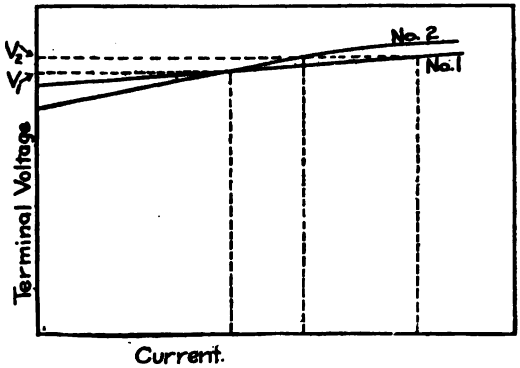


Fig. 35.

In order that the machines may divide the load equally their characteristics must be the same and in addition the resistances of the series coils must be adjusted so that there will be no flow of current through the equalizer which connection puts the series coils in parallel.

In order that no current shall flow in the equalizer, the drop of potential through the series coils of all the machines must be equal when each series coil carries the rated current of its machine. If R_1, R_2, etc., represent the resistance of the series coils of several generators and I_1, I_2, etc., represent their rated currents, the following relation must hold if the current in the equalizer is to be zero.

$$I_1R_1 = I_2R_2 = I_3R_3 \text{ etc.,}$$

$$\text{or } \frac{1}{R_1} : \frac{1}{R_2} : \frac{1}{R_3} \text{ etc.,} = I_1 : I_2 : I_3 : \text{etc.}$$

for two machines $\quad \dfrac{R_1}{R_2} = \dfrac{I_2}{I_1}$

If the machines are of the same size R_1 should equal R_2.

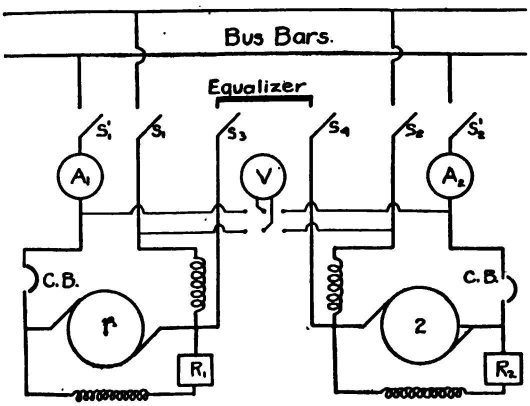


Fig. 36.

Any two compound generators in parallel will be stable provided there is an equalizer. They cannot, however, be made to share the load properly without current flowing in the equalizer unless their characteristics are similar and the resistances of their series coils are inversely proportional to their rated current outputs.

The proper connections for the parallel operation of two gen-

erators are shown in Fig. 36. These connections can be extended for any number of generators. For this test, an ammeter should also be placed in the equalizer circuit.

Suppose generator No. 1 is in operation, switches S_1 and S_1' being closed. To throw in generator No. 2, first bring it up to speed, then close the equalizer switches S_3 and S_4 and adjust the voltage of generator No. 2 until it is approximately the same as that of generator No. 1. Close the switch S_2 connecting the series coil of the other incoming machine to line. This will cause a drop in the line potential due to shunting part of the current from series coil of the other generator by the series coil of generator No. 2. This drop should be corrected by adjusting the shunt field of No. 1. Now adjust the voltage of the incoming generator, No. 2, until it is the same as that of the bus-bars, then close switch S_2'. The generators will now be in parallel but generator No. 2 will have no load. There will be, however, current in the series coil of generator No. 2 supplied through the equalizer from the other machine. The load on No. 2 may now be increased until it takes its proper share by slowly increasing its shunt field current. The shunt field current of the other generator should also be changed to keep the line potential constant. To take the generator out of circuit, the load on it should be reduced to zero and the switches S_2' S_2, S_4 and S_3 opened in the order named, and the line potential adjusted by field rheostat of No. 1.

The equalizer switch must always be closed before both terminals of a generator are connected to the bus-bars, and must never be opened until at least one terminal of the generator has been disconnected from the busses.

If the generators are not over compounded the switches S_2' and S_2 may be closed together and may be replaced by a single double-pole switch. The switches S_2', S_2 and S_4 may even be combined into a single three-pole switch provided the blade of S_4 is slightly wider than the blades of S_2' and S_2 so that the equalizer connection is made first when the three pole switch is closed.

The ammeters must be placed so as to indicate the actual output of the generators, and, therefore, must be placed so that their readings will not be influenced by any current which may be flowing through the equalizer. The best position for the ammeters is shown in the diagram of connections, Fig. 36. If, for any reason, they are placed in the main containing the series coil, they must be placed between the armature and the equalizer connection.

Test.—Connect the two generators as in Fig, 36, being sure that the equalizer and series coils are properly arranged.

Bring both generators up to speed and voltage and test the polarity of each to see that it is the same.

Carefully adjust the brushes, then take the compound characteristic of each machine separately, starting each character-

istic at the voltage at which the machines are to be run when in parallel.

Take the load off of both generators and then put them in parallel at no load. Increase the load on the system until either generator delivers full load current. Record the current output of each generator, the line voltage, and occasionally the speeds as the load is increased.

Reduce the load until it is a little less than the full load of one generator, then take one machine out of service.

Following the directions already given put this generator back in parallel with the one already loaded. Notice the effect on the voltage of the system and the current in the equalizer, if an ammeter for the equalizer circuit is provided, when the switch connecting the series coil to the line is closed. Notice the effect on the voltage of the system of attempting to make the generator take load without adjusting the rheostat of the loaded machine.

Try shifting the load from one machine to the other: first, by adjusting the rheostat in the field of one machine alone, then, by adjusting both field rheostats.

Results required:—Plots of the compound characteristics and speed curves of each generator and a plot showing the distribution of load between the two when in parallel. The abscissae for all curves should be current. In addition the report should contain a brief discussion of the results of the experiment.

XIII

DYNAMOTOR

A dynamotor consists of a shunt machine with two commutators each connected to independent armature windings. One of the armature windings and the shunt field are used as a shunt motor. The other armature winding acts as a generator.

Dynamotors are used to transform direct current from one voltage to another, in cases where the ability to regulate the voltage is unimportant. They are more efficient than motor-generators, since they require only one field and one armature, but have the distinct disadvantage of a fixed voltage ratio. Nothing which is done to either speed or field will alter this ratio, since both motor and generator windings are on the same armature and rotate in the same field.

The ratio between the armature voltages will depend solely upon the ratio of the number of turns, on the two armature windings, while the ratio between the impressed and terminal voltages at any load will depend upon the ratio of the armature voltages and upon the resistance drops in the motor and generator windings.

If PD and E represent respectively the terminal voltage of the generator winding, and the impressed voltage on the motor, and the subscripts *g* and *m* refer to the generator and motor, respectively,

$$P\,D = (E - I_{ma}\,R_m)\,\frac{N_g}{N_m} - I_g\,R_g$$

where N_g and N_m are the numbers of turns on the two windings.

If there were neither armature nor friction losses the input to the motor armature would be equal to the output of the generator armature, the ampere turns of the two armatures would be equal and opposite and the armature reaction would be zero. Since the losses in a good dynamotor are small, this condition is nearly realized.

Therefore no movement of the brushes with change in load is required. The brushes need only be displaced far enough from the neutral point for commutation.

The rating of the machine should be obtained from its name plate.

Connect the motor side of the dynamotor as a shunt motor with a starting box. The generator winding should be connected to a bank of lamps, or other suitable resistance load. An ammeter and a voltmeter should be placed in each circuit. The proper connections are shown in Fig. 37.

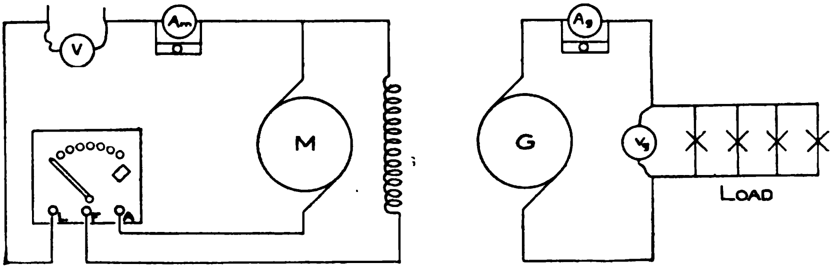


Fig. 37

S = shunt field
M = motor commutator
G = generator commutator

When the dynamotor has been connected properly, start it as a shunt motor. Take readings of the speed and all the instruments. Ammeter A_g should read zero. Apply load to the generator winding and take readings of speed, current, and voltage (both of the generator and of the motor side) for about eight to ten loads from no load to twenty-five per cent overload.

When this has been done, stop the dynamotor and measure the resistances of the two armature circuits and the shunt field by the drop-of-potential method. Include the resistance of the starting box with its arm in the running position in the resistance of the motor armature. This box is a necessary part of the machine and any resistance in it should be included in the motor resistance.

The report on this experiment should contain a plot of curves of commercial efficiency, i. e.,

$$\frac{A_g V_g}{A_m V_m}$$

generator voltage, and speed, all plotted with generator current as abscissae.

A curve should also be plotted between the generator voltage calculated by the formula given on page 47, and generator current. In this formula

$$\frac{N_g}{N_m} = \frac{V_g}{V_m - I'_m R_m}$$

where V_g and V_m are the no load voltages of the generator and motor respectively, and I'_m is the no-load armature current of the motor side. This no-load armature current may be found by subtracting the current in the shunt field from the no-load motor current. The current in the shunt field may be measured, or it may be obtained by dividing the impressed voltage by the shunt field resistance.

In the formula on page 47, I_{ma} may be taken as approximately equal to

$$I_g \frac{N_g}{N_m} + I'_m$$

The approximation is the assumption that the part of the motor current, I'_m which is used in supplying the no-load losses, remains constant and independent of the load.

XIV

METHODS OF SPEED VARIATION OF A SHUNT MOTOR.

The current through the armature of a shunt motor is equal to the difference between the impressed electro-motive force and the back electromotive force of the armature, divided by the armature resistance. This back electromotive force, or armature potential as it is called, is caused by the armature conductors cutting across the lines of force of the field.

If E is the impressed potential and E_a is the armature potential, the current in the armature is given by

$$(1) \qquad I_a = \frac{E - E_a}{R_a}$$

where R_a is the armature resistance. It follows from this expression that the armature potential of a motor is equal to the impressed potential minus the product of the armature current into the armature resistance.

$$(2) \qquad E_a = E - I_aR_a$$

According to Ohm's law, I_aR_a represents the drop of potential through the armature due to the armature current, I_a, flowing through the armature resistance, R_a.

The electromotive force generated by the movement of a conductor across a magnetic field is proportional to the strength of the field and to the speed at which the conductor moves. Since the armature of a motor consists simply of a series of conductors revolving in a magnetic field, it follows that the back electromotive force set up in it as it revolves, (that is, its armature potential), must be proportional to the speed with which its conductors move and to the strength of field in which they revolve.

The armature potential is then equal to

$$E_a = k \phi s$$

where *k* is a numerical constant, depending upon the number of armature conductors, number of paths in the armature the strength of the magnetic field in which the armature revolves, and *s* the speed of revolution.

Combining this with Equation (2)

$$E_a = K\phi S = E - I_a R_a$$

Solving for S

$$(4) \qquad S = \frac{E - I_a R_a}{K\phi}$$

There are three variables in this expression for speed, E, I_a, and ϕ.

If a shunt motor is run on constant potential mains, E will be constant. Since the field is connected across constant potential mains, ϕ which depends upon the field current will also be constant except in so far as it may be influenced by the current in the armature reacting on the field. In a well designed motor this reaction will be small so that ϕ may be assumed constant. The only thing which can change the speed under the above conditions is the armature current. This will increase as the motor is loaded, causing the term I_aR_a to increase and the speed to diminish.

It is readily seen from what has been said that if the change in speed from no load to full load is to be small the term I_aR_a must be small. The only way this can be made small for a given size of motor is to make the armature resistance as small as possible. This is always done.

Suppose the resistance of the armature of a 230-volt motor is 0.4 ohms and its full armature current is 50 amperes, the speed at full load will be

$$S = \frac{E - I_a R_a}{k\,\phi}$$

$$= \frac{230 - 20}{k\,\phi}$$

At no load I_aR_a will be very small, not more than 1.5 volts. If E is constant the field current and consequently ϕ will be constant. The only change in speed which occurs must be due to the change in the numerator of the above equation. This will be

$$20 - 1.5 = 18.5, \text{ or}$$

$$(5) \qquad \frac{18.5}{230} = 8\%$$

It is readily seen from this why a shunt motor will not race when the load is thrown off.

It is often necessary to change the speed of a shunt motor in order that it may be used for some special piece of work. This may be done in two ways, either by changing the field strength by variation of the field current, or by putting resistance into the armature circuit. This latter is equivalent to increasing the armature resistance.

Variation of ϕ. — If ϕ is changed, the speed of the motor will be changed in the inverse ratio, i.e. an increase in ϕ will produce a corresponding decrease in speed, and vice versa. Since ϕ is dependent upon the field current, an increase in this current will cause the motor to slow down, while a decrease will cause it to speed up.

The speed regulation of the motor, viz., its change of speed from no load to full load, will not be changed since it does not affect the term I_aR_a upon which speed regulation is dependent.

Most motors are built to run without a field rheostat. In this case it will be impossible to slow the motor down by increasing the field current. It may be speeded up, however, by putting resistance in the field circuit and in this way decreasing the field current. It is seldom safe to increase the speed of a motor more than 25% above its rated value and even if it were, it probably could not be done on account of the tendency of an ordinary motor without commutating poles to spark under load, if run with a weak field.

Variation of resistances placed in the Armature Circuit:

$$S = \frac{E - I_aR_a}{k\,\phi}$$

When I_a is small, as under light loads, a change in R_a will have very little effect on the speed but if the motor is loaded so that I_a is large, a small change in R_a will make a very marked change in speed.

Suppose it is desired to reduce the speed 50% at full load current. In order to do this —

$$\frac{I_aR_a}{E}\,100 \text{ must } = 50$$

$$\text{or} \qquad I_aR_a = \frac{E}{2}$$

The full load current was 50 amperes. Solving the above equation for R_a and substituting the values of I_a and E.

$$R_a = \frac{E}{2\,I_a} = \frac{230}{2 \times 50} = 2.3 \text{ ohms. *}$$

It is impossible to increase the armature resistance, R_a, but adding resistance to the armature circuit will have the same effect.

The speed regulation in this case will be very poor. Suppose the load is thrown off. The armature current to run a motor of this size at no load will be about four amperes. For no load I_aR_a will be $4 \times 2.3 = 9.2$ volts, while the value of the voltage drop for full load current will be $50 \times 2.3 = 115$ volts.

The percentage change of speed from no load up to full load current will be

$$\frac{115 - 9.2}{230} = 45.$$

as against 8 under normal conditions. Aside from the poor speed regulation this method gives, it is very uneconomical, since it involves a large amount of energy wasted in the resistance placed in series with the armature. In the case assumed, half of the energy supplied to the motor is wasted.

* In these equations R_a may be considered to be the total resistance through which the current I_a flows.

There is still another method by which the speed of a motor may be reduced. This is by varying the voltage E, applied to the armature circuit. This may be done by supplying current to the armature from storage batteries, but these are often not available.

If the motor is run on a three-wire system, its speed may be reduced to approximately one-half by supplying current to its armature at half voltage, as shown in Fig. 38.

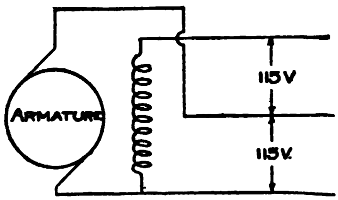


Fig. 38.

This method is economical, and at the same time gives good speed regulation. For example: Suppose the motor used in the previous examples has its armature put on half voltage by connecting it between the neutral and one outside wire of the three-wire system. E will be 115 and the speed regulation will be —

$$\frac{18.5}{115} = 16\%$$

as compared with 45 by the previous method.

Aside from the better speed regulation this last method involves no waste of energy in resistance, as does the former.

If this last method is used, precautions must be taken to prevent injury to the field when its circuit is opened. If the machine is small there will be little danger. If it is large, however, a high resistance shunt should be placed about the field terminals to take the discharge from the magnet when the field circuit is opened. Ordinarily, when the circuit of a shunt motor is opened, the armature acts as a generator supplying current to its field causing the field current to decrease slowly as the machine slows down.

Test. — An ordinary shunt motor, or preferably a motor with commutating poles will be used for this experiment. Load will be applied either by a friction brake or by belting the motor to a generator which may be loaded with a resistance load. A rheostat for varying the motor speed by armature resistance and a suitable field rheostat will be provided in addition to the ordinary starting box.

Procedure. — Cut out all the resistance in the field rheostat. Make sure that the brushes are set properly and then start the motor. Adjust the field rheostat to give the maximum speed at which it is safe to operate the motor. Ask what this speed is, unless a variable speed interpole motor is used, in which case the maximum speed should be found on the name plate.

Load the motor, taking about eight readings of current and speed between no load and full load. The speed can best be obtained by means of some form of direct-reading tachometer.

Throw off the load and adjust the motor field for minimum speed and repeat the above set of readings.

A third run should be made with the motor field set for the maximum speed, but with enough resistance inserted in the armature circuit to give the same speed at full-load current that the motor had at full load in the second run. Throw off the load leaving the rheostats unchanged and take a third set of readings of speed and current as load is applied.* Take about eight sets of readings between no load and full-load current.

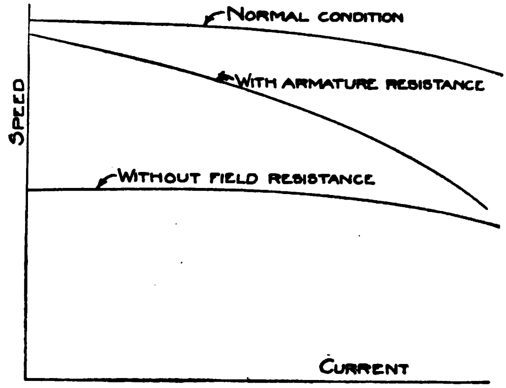


Fig. 39

The data obtained from the three runs should be plotted to the same scale, with currents as abscissae and speeds as ordinates. The three curves are plotted on the same sheet as shown in the diagram, Fig. 39.

*If the speed of a motor is to be reduced by reducing the armature voltage, it will be impossible to still maintain the same horse-power output since this would involve an increase in the motor current beyond its rated value and consequently overheating.

XV

ELECTRICAL SUPPLY OF LOSSES

In the ordinary stray-power method of determining the efficiency of a direct-current generator or motor, the losses are measured with the machine running idle as a motor. The method of Electrical Supply of Losses measures the losses under full-load conditions. The disadvantage of the method is that two similar machines, connected by a mechanical coupling are required.

The proper connections for supplying the losses electrically under load conditions are shown in Fig. 40.

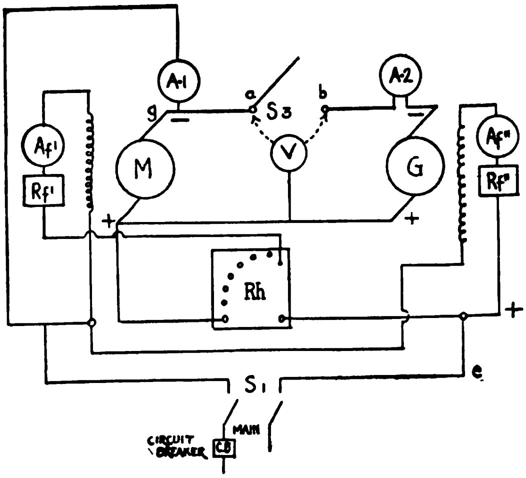


Fig. 40

S_1 is the main switch and C B a circuit breaker. The field ammeters are shown at A_f' and A_f''. R_f' and R_f'' are the field rheostats.

Procedure.—Connect the machines as shown in the diagram. See that the brushes are in the proper position for no load, then, with S_3 open and all the resistance cut out in the field of the machine used as a motor, close the breakers and switch S_1 and slowly start the motor by means of the starting rheostat. If the motor does not start with the rheostat on the second or third notch, assist it by hand. If it attempts to rotate in the wrong direction, open the switch S_1 and reverse the motor field connections.

Do not shut the motor down by allowing its starting rheostat to come back to the starting position, as this will cause the rheostat to arc and badly burn the contacts. Always stop the motor by opening the line switch. The machine will then run as a self-excited generator; as it decreases in speed the field strength will decrease until the force of the hold-up magnet is no longer sufficient to resist the spring on the starter handle, and the handle returns to starting position.

Bring the motor up to its rated speed by slowly weakening the field. Adjust the generator voltage until it is equal to the motor voltage, and of the same polarity with respect to the mains.

The voltage of the mains should be measured by touching the free lead of the voltmeter *v* to the point marked *a*. If this lead is connected to *b* the voltmeter will give the generator voltage. The polarity of the generator should be opposed to that of the mains, i. e., if the point *a* be positive, *b* should also be positive. If the deflection of the voltmeter does not reverse when its connection is changed from *a* to *b*, it shows the polarity of the generator is right. If the polarity of the generator is wrong, shut the system down and reverse the field of the generator.

When the voltmeter reads the same whether it be connected to *a* or *b*, close the switch S_3. This puts the two machines in parallel. If the voltage is properly adjusted, no current should flow in the armature of the generator.

The generator can be loaded by slowly increasing its field and at the same time weakening the field of the motor in order to keep the speed of the system constant.

If the machines are without interpoles, as the system is loaded the position of the brushes will have to be changed to correspond to the change in the load. The motor brushes must be moved backward (against rotation) with increasing load. This will increase the speed and hence the load on the generator. The generator brushes must be moved forward as the machine is loaded. This will decrease the potential of the generator and cut down the load. The brushes on both machines must be moved slowly and only a little at a time, allowing the machines to settle down to the new condition before changing the brushes again. Be sure that the brushes are firmly locked before letting go of the handle, by means of which they are moved.

When the system is loaded, the motor will deliver mechanical power to the generator through the coupling between the two machines while the generator in turn will deliver electrical power to the motor. The difference between these powers represents the armature losses in the two machines. These losses will be supplied electrically from the external mains.

The load on the generator is indicated by the reading of ammeter A_2, while the current supplied to the system to make up for the losses is given by A_1.

Load the system until the generator ammeter, A_2, indicates full-load current. The motor will be considerably overloaded since it carries the current delivered by the generator plus that necessary to supply the losses in the system.

Allow the machines to run until the conditions become reasonably constant. Five or six hours would not be too long in an actual test, but here ten or fifteen minutes will have to suffice, then take several readings of all the instruments, viz., A_1, A_2, A_f', A_f'', and V. The speed of the system should also be recorded.

When the above readings have been taken, shut the system down by first taking the load off the generator, by carefully weakening its field, then opening the switch S_3, and finally opening the circuit breaker CB and the switch S_1.

The resistance of both armatures must now be measured, useing the drop-in-potential method. To do this first, disconnect the fields of the machines in order that they will not turn when current is passed through their armatures. Disconnect the wire marked e in Fig. 40, and insert a resistance in its place.

If, with S_3 open, the circuit breaker CB and the switch S_1 be closed, current will pass only through the motor armature. If now the voltmeter be connected to the terminals of the motor, i. e., connected to *a*, its reading divided by the readings of A_1 will give armature resistance of the motor. This ought to be measured with the armature in a number of different positions and if possible with full-load current.

Open CB and S_1, then break the circuit of the motor at any convenient point, such as *g*. If S_3 be now closed, current will flow only through the generator armature when CB and S_1 are closed. The reading of the voltmeter divided by the reading of A_1 will now give the generator armature resistance. This should also be measured with the armature in several different positions and if possible with full-load current.

Calculations.—Let the letters used on the figure to indicate the instruments, represent their readings when the generator delivers full-load current.

$A_1 \times V$ will be equal to all the losses in the system with the exception of the heating or I^2R losses in the fields.

The product A_1V is then the heating loss in the two armatures, viz., $A_2^2R_g + (A_1 + A_2)^2R_m$, plus the total stray power of the system.

The total stray power is then given by

$$A_1V - (A_2^2R_g + (A_1 + A_2)^2R_m)$$

where R_g and R_m are the generator and armature resistances respectively.

Since the stray power of most machines at a constant speed varies nearly as the armature voltage, the total stray power of the system should be divided between the two machines directly as their armature voltage.

The armature voltage of the motor is

$$V_m = V - (A_1 + A_2)\ R_m,$$

The armature voltage of the generator is

$$V_g = V + A_2R_g.$$

The stray power of the generator is equal to

$$(\text{Total S. P.}) \times \frac{V_g}{V_g + V_m}$$

Efficiency of Generator.—The efficiency of the generator will be its output divided by its output plus all of its losses. The losses will be its stray power, the heating loss in its armature, and the heating loss in its field.

$$\text{Efficiency} = \frac{A_2V}{A_2V + (A_2 + A_f'')^2R_a + A_f''V + \text{S. P.}}$$

$(A_2 + A_f'')$ is the current in the generator armature under ordinary working conditions, when the external current is A_2. $A_f'V$ is the loss in its field.

Results Required:—Table of data including the resistances of the armatures of both machines and the efficiency of the generator at full load.

Since by this method it is possible to run a generator or motor under full load conditions and yet consume only a small amount of power, the method of "Electrical Supply of Losses," is well adapted to make a heat run, provided a second machine of the same, or a little higher size than the one to be tested, is at hand. Unless the machines are identical, the stray power of the system cannot be divided between them and their efficiencies, therefore, cannot be found.

XVI

THE DETERMINATION OF THE CANDLE POWER OF AN INCANDESCENT LAMP.

The unit of light used in the United States is the English standard candle, and is the light given out in a direction perpendicular to the axis of the flame of a spermacetti candle, seven-eighths of an inch in diameter, weighing one-sixth of a pound, and burning at the rate of 120 grains per hour.

The candle is a very unsatisfactory standard and is much inferior in regard to the constancy and the certainty with which it can be reproduced, to the German standard, viz., the Amyl Acetate, or Hefner lamp, as it is called. The German unit is called the Hefner.

The adoption of this standard was recommended by the International Electrical Congress in 1893. No action, however, has ever been taken by which it has been legalized in the United States.

The Hefner lamp, although still far from a satisfactory standard, is the simplest and probably the most reliable of the various forms of light standards now in use. It has been very carefully studied by the Reichsanstalt (testing bureau of the Prussian government) and the corrections to be applied to it for atmospheric conditions are known. As a result of a great many comparisons it was found equal to 0.88 English standard candles.

The lamp is a very carefully constructed spirit lamp of specified dimensions burning pure amyl acetate with an open flame 40 millimeters high.

A committee of the American Institute of Electrical Engineers recommends the adoption of this lamp as a standard, provided it is certified by the Reichsanstalt.

Both the standard candle and amyl acetate lamp are of too small intensity, and require too much attention to be used except as ultimate standards of reference.

The best secondary, or working standard is a well made incandescent lamp burnt at a constant voltage or constant current. Such lamps, of course, have to be calibrated in terms of some primary standard, as, for example, a standard candle. These are simply carefully made lamps which have been calibrated at some definite voltage and in some definite position. In this experiment a standard incandescent lamp which was calibrated by comparing it with a Hefner lamp, will be used.

A standard incandescent lamp has the great advantage of being entirely free from atmospheric disturbances, but it must be very carefully used and its voltage never allowed to exceed its

rated value. The intensity of an incandescent lamp will not change except while the lamp is in use. The way in which the candle power* of most lamps varies with the length of time they are burnt is shown roughly in the following diagram, Fig. 41.

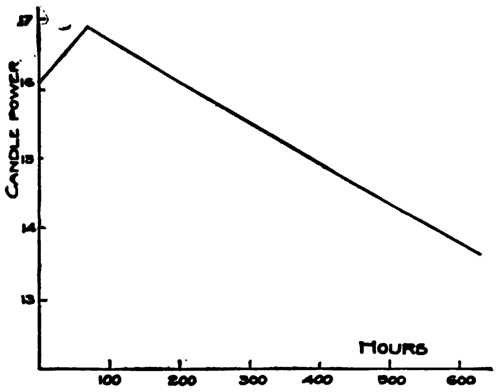


Fig. 41

There is a period at the beginning of the life of most lamps during which the candle power varies quite rapidly, but after this period is passed there should be a slow decline in candle-power as the lamp is burnt. A good lamp should not decrease in candle-power by more than 20% in 600 hours. A lamp should never be used as a standard until it has passed the first period shown on the curve. For this reason, a lamp should be aged by burning it a number of hours before attempting to calibrate it.

It is evident from the preceding that, although an incandescent lamp can be used a considerable number of hours without material change in candle-power (30 hours would probably cause a change of about one per cent), it cannot be run continuously without sensible change in the amount of light given out.

If no means are at hand for re-calibrating a standard incandescent lamp, it should be used only as a standard of reference, calibrating working standards from it. The calibration of these standards should be checked up from time to time.

Since the intensity of an incandescent lamp varies greatly with the direction in which it is measured, standard lamps must be calibrated and used in some definite position. This position must be clearly indicated on the lamp.

The candle power of an incandescent lamp varies much more rapidly than the voltage; that is, if the voltage at the terminal of a lamp is increased by one per cent., the candle-power of the lamp will be increased by very much more than one per cent. The change is nearly as the fifth power of the voltage. For this reason, in all work on incandescent lamps, the voltage must be held within one or at the most two tenths of one per cent, that is, the voltage of a 100-volt lamp, should not be allowed to vary more than 0.1 volt. Besides the very great increase in candle-power caused by an increase in voltage, an increase in voltage will cause a rapid decline in the length of life of the lamp.

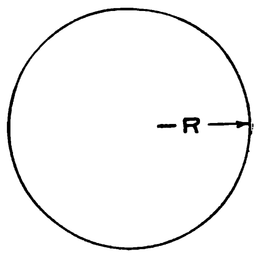
* By candle power is meant the number of standard candles which will exactly replace a lamp.

Photometer.—A photometer is an instrument for measuring the relative intensity of two lights. The eye cannot judge the relative intensity of two lights. It can, however, judge with considerable accuracy when two adjacent surfaces are equally illuminated.

All photometers are based upon the production of equal illumination upon two surfaces placed so that each is illuminated by one of the two lights to be compared. The most common way of varying the illumination of the surfaces so that equality may be produced is by moving the lights nearer or further away from the surface which they illuminate. If the perpendicular distances between the surface and light is measured, the relative intensity of the lights may be calculated.

The intensity of illumination on a surface, i.e., its brightness, varies inversely as the square of the distance of the surface from the light which illuminates it.

The intensity of illumination of a surface is equal to the quantity of light it receives per unit area. It can easily be shown that that this varies as the inverse square of the distance. For example,—suppose ϕ is a luminous point. If Q is the quantity of light given out by the point, all of this light must pass through any enclosing sphere having its centre at the point. Call the radius R. The intensity of illumination on the sphere will then be the quantity of light Q divided by the surface over which it is spread, or the area of the sphere.



$$I = \frac{Q}{\text{area}} = \frac{Q}{4\Pi R^2}$$

Fig. 42

If the radius of the sphere be increased, the intensity of its illumination will vary as the inverse square of its radius, or inversely as the square of the distance between the source and the surface.

The arrangement of the Bunsen photometer is shown in Fig. 43.

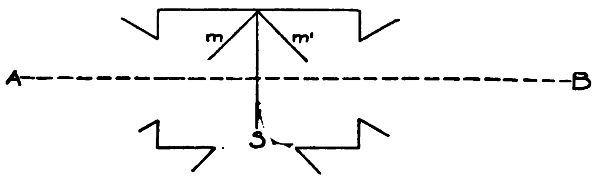


Fig. 43

Carriage.—The two lights A and B, which are to be compared, are placed at opposite ends of a graduated bar. A small carriage, mounted so that it can be moved along the bar, is placed between the lights. This carriage carries the screen S, one side of which is illuminated by the light A, the other side by the light B. By the use of two mirrors, *m* and *m'*, both sides of the screen can be seen at once through the opening in the carriage.

The carriage is moved back and forth until both sides of the screen appear equally bright, then, if *A* and *B* represent the intensity of the two lights in candle power, and *a* and *b* their distance from the screen, *I*, the intensity of illumination on the screen will be

$$\frac{A}{a^2} = \frac{B}{b^2}$$

If *A* is a standard light of *B* candle-power, the candle-power of *A* will be

$$A = B\left(\frac{a}{b}\right)^2$$

If the distance between the two lights is fixed and equal to *X* and the graduated bar or scale is placed with its zero at *B*, the distance a will be equal to (*X*-*b*) and

$$A = B\left(\frac{X - b}{b}\right)^2$$

A common length for *X* is 100 inches. Instead of reading the distance *b* on the scale and calculating the ratio

$$\left(\frac{x - b}{b}\right)^2 = R$$

each time, this ratio may be calculated for each point on the scale once for all, and marked on the bar. The position of the screen S, as indicated on this scale, multiplied by the candle-power of the standard will give the candle-power of the unknown lamp.

Screens:—The Bunsen screen consists of a piece of white paper, the centre of which has been rendered translucent by means of paraffine or other suitable material. A medium weight, smooth, bond paper will answer very well.

If such a screen is illuminated from behind, more light will pass through the centre or greased portion than through the outside. The centre will then appear brighter than the outside. If the screen is illuminated from the front, less light will be reflected from the greased centre than from the ungreased outside. In this case, the centre will appear dark,

If such a screen is placed between two lights, the greased centre will appear dark on the side which receives the most light. If, now, the screen is moved back and forth between the two lights, the centre will appear dark first on one side and then on the other. When the illuminations upon the two sides of the screen are equal, the two sides will appear the same, with the greased spot very slightly darker than the rest of the screen.

Rating of Incandescent Lamps: — The distribution of light about an incandescent lamp is never uniform, but varies greatly according to the direction in which it is measured. The distribution of light about a lamp with a spiral filament is much more uniform than the distribution about a lamp with a straight filament, but it is still far from uniform.

A comparison of the illuminating power of various incandescent lamps should be made between their mean candle power; that is, the average of the candle-powers measured in all possible directions about the lamp, or the mean spherical candle-power as it is called.

This is never done commercially. All lamps are rated on the mean candle-power measured in a plane through the centre of the filament perpenicular to its axis. This would be the mean of the candle-powers measured in a horizontal plane, provided the lamp were placed with its axis vertical. For this reason it is called the mean horizontal candle-power.

The efficiency of a lamp as expressed for commercial purposes is the number of watts per mean horizontal candle-power. For example, a 16 C.P., 3-watt lamp is one which has a mean horizontal candle-power of 16 candles, and consumes 16 x 3 = 48 watts, or 3 watts for each horizontal candle power. The mean spherical candle-power of an ordinary 16 candle-power lamp will be in the neighborhood of 12 candles. This will, of course, vary greatly with the shape of the filament.

The distribution of the light about an incandescent lamp is best shown graphically by curves giving the distribution in the horizontal plane (axis of the lamp vertical) and four vertical planes making angles of 0°, 45°, 90°, and 135° with a vertical plane through the axis of the lamp perpendicular to the line joining the shanks of the filament.

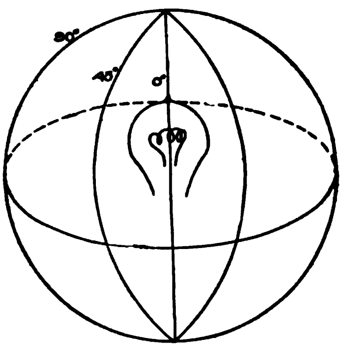


Fig. 44

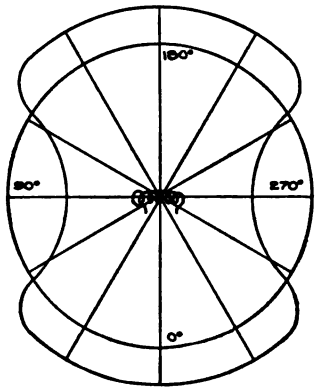


Fig. 45

The horizontal distribution may be obtained by putting the lamp in a vertical position and measuring its candle power as it is rotated about a vertical axis 30° at a time. The horizontal distribution of most lamps will be similar to Fig. 45. The candle-powers are plotted radially outward from the centre.

The circle represents the mean horizontal candle-power. This is the mean of the candle-power measured in the horizontal plane and therefore the mean of the lines plotted on Fig. 45.

The mean horizontal candle-power may be more readily obtained by placing the lamp in a vertical position and rotating it about its axis about six times a second. The illumination on the photometer screen then will be the mean of the illumination produced by the lamp as it rotates, and the photometer will give the mean horizontal candle-power directly.

Test:—The results required are the mean horizontal candle-power by rotation, and the distribution in the horizontal plane plotted from readings taken every 30°. If the time will permit, also take the distribution in the vertical plane which is perpendicular to a line joining the shanks of the filament. This is the plane marked zero in the figure. An incandescent lamp which has been calibrated against a Hefner lamp will be used as a standard. The voltage at which this must be run, and its candle-power are indicated on the lamp. The arrow on the top of the lamp must point directly toward the photometer screen.

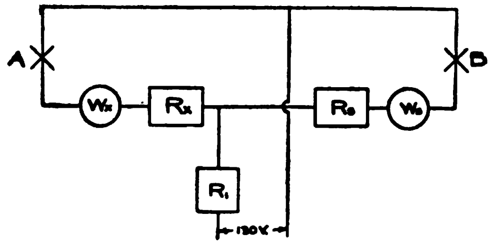


Fig. 47

The electrical connections are shown above.

R_1, R_x, and R_s are variable carbon resistances: W_x and W_s are resistances for coarse adjustment.

R_1 will affect the potential of both lamps, while R_s and W_s will affect principally that of B, and R_x and W_x principally that of A. By proper adjustment of these resistances, the lamps may be brought up to their proper voltage. A voltmeter is arranged so that it may be connected by switches to either lamp, or so as to give the difference in the voltage between them.

Procedure:—Place the standard lamp in the holder in the box at the right hand end of the photometer. Put the lamp to be tested in the holder at the other end. This second holder is arranged so that the lamp may be rotated by hand about either its own axis or about a horizontal axis. It may also be rotated about its own axis by a small motor. The amount of rotation is read on divided circles.

Place the lamp in a vertical position, and adjust it so that the centre of the filament is in a line through the centre of the photometer screen, i. e., in the axis of the photometer. Now loosen the set-screw which locks the divided circle to the shaft carrying the lamp, then place the lamp so that the plane of the shanks of the filament is perpendicular to the axis of the photometer and at the same time set the zero of the divided circle opposite the index, then tighten the set-screw. This fixes the lamp.

Loosen the carbon rheostats and close the main switch. Connect the voltmeter to the standard lamp, then slowly bring its voltage up to the value marked on the lamp by tightening the carbon rheostats, R_1 and R_s. If a very moderate pressure will not bring the lamp up to voltage, cut out some of the resistance in rheostat, W_s. Be carefull not to allow the lamp to go above the proper voltage. When the voltage of the standard lamp has been adjusted, bring up the voltage on the other lamp by adjusting R_x and if necessary, W_x. Readjust the potential of the standard. Then connect the voltmeter so as to give the difference in voltage between the two lamps. This should be the difference between the rated voltage of the two lamps. If it is not, make it so by adjusting either R_x or R_s.

If this difference is small (that is, the two lamps to be tested are of about the same voltage) and is kept constant, any slight fluctuation in the line voltage will affect the voltage of both lamps by nearly the same percentage amount. This will cause both lamps to change their candle-power in very nearly the same proportion and hence their ratio will remain unchanged.

Having adjusted the voltage, make several settings of the photometer. Connect the voltmeter so as to give the voltage of the lamp being tested. If it is not at the proper value, adjust it by R_1, then read the ammeter. This is connected so as to measure the current in the test lamp.

Connect the voltmeter again to read the difference in voltage and, if necessary, adjust the carbon rheostats.

Rotate the test lamp through 30° and take another set of readings. Take readings of the photometer, voltmeter, and ammeter for each 30° rotatation through 360°. The last reading should check the first. These will give data for plotting the horizontal distribution.

The mean of all the candle-powers found, except the last, will give the mean horizontal candle-power of the lamp. Now start the motor which rotates the lamp and take a series of readings for the mean horizontal candle-power. Eight or ten settings of the photometer should be made in order to get a fair average value.

Keep the difference in the voltage between the lamps constant and at the same time keep the unknown lamp as near its rated value as possible.

From the value of the mean horizontal candle-power found, and the average ammeter and voltmeter readings, calculate the efficiency of the lamp in watts per mean horizontal candle-power.

NOTE— While making settings of the photometer do not look at the lamps or other bright objects.

XVII

A. C. CIRCUITS CONTAINING RESISTANCE CAPACITY AND INDUCTANCE.

Series Circuit: — In a direct current series circuit, the current is the same in all parts and the sum of the voltage drops across the circuit is equal to the impressed voltage. The voltage drop in any one of the components must always be less than that across the entire circuit.

In the case of an alternating current series circuit the conditions are similar provided the voltages are added geometrically as vectors. The current at any instant is the same in all parts of the circuit, and the vector sum of the voltage drops across the component parts of the circuit is equal to the total impressed voltage. If the circuit contains both capacity and self-inductance, the voltage drop across either the capacity or the self-inductance, or across each may be greater than the voltage impressed on the circuit.

The current in a series circuit containing resistance, self-inductance and capacity is given by the following expression:

$$I = \frac{E_0}{\sqrt{R^2 + (Lp - 1/Cp)^2}}$$

where L and C are, respectively, the self-inductance and capacity, and p is equal to $2\pi f$ with f the frequency of the impressed e.m.f. R represents the total effective resistance of the entire circuit.

$Lp = x$, is the reactance due to self-inductance or generally simply reactance, $I/Cp = x'$ is the capacity reactance. Reactance multiplied by the current gives the voltage necessary to overcome the e. m. f. of reactance just as the resistance of a circuit multiplied by current gives the e. m. f. necessary to overcome the drop in potential due to resistance.

The current in a circuit containing nothing but resistance is in phase with the impressed voltage. If the circuit contains only self-inductance, the current will be 90° behind the impressed voltage while if it contains nothing but capacity the current will be 90° ahead of the voltage. Since the effect of capacity and self-inductance are opposite, in so far as lead and lag are concerned, the reactances due to them are written with opposite signs. Reactance due to self-inductance is considered positive; that due to capacity negative. The equation given above may be written

$$E_0 = I_0\sqrt{R^2 + (x - x')^2}$$

The power consumed in any circuit is always given by $E_0I_0\cos\theta$, where θ is the angle of lag or lead of the current behind the voltage and E_0 and I_0 are the impressed voltage and current. Since

θ due to either pure capacity or pure self-inductance is 90°, the power lost due to either is zero.

— Diagrams for a Series Circuit—

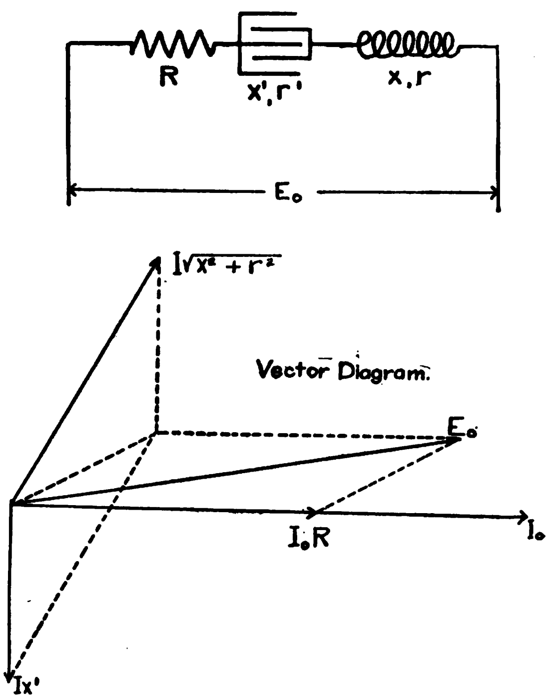


Fig. 48.

Condensers and reactance coils cannot be made without some resistance. This causes a loss due to I^2R. The presence of iron in reactance coils also causes more or less loss. On account of these losses, the phase difference between the currents and the voltages in condensers and reactance coils will not be quite 90°, but will be enough less to give a component of the voltage along the current to supply the losses.

The actual voltage drop across capacities and reactances will be given by $I_0\sqrt{x'^2 + r'^2}$ and $I_0\sqrt{x^2 + r^2}$ where r' and r are the effective resistances. The expressions $\sqrt{x'^2 + r'^2}$ and $\sqrt{x^2 + r^2}$ are called the impedances. The energy lost will be given by the current squared multiplied by the resistance. I_0 is the current in the circuit and E_0 is the impressed voltage. E_0 is equal to the vector sum of the voltage across the resistance, I_0R, the voltage across the condenser, I_0x' (r' assumed to be zero,) and the voltage across the reactance coil, $I_0\sqrt{x^2 + r^2}$.

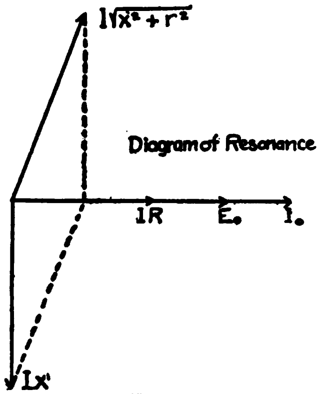


Fig. 49.

From the diagram it can readily be seen that the voltage across either the condenser or the reactance may be greater than the impressed voltage.

When the wattless components of the voltages across the condenser and reactance are equal the circuit is said to be in reson-

ance and the current follows Ohm's Law. The wattless components are the components perpendicular to the current.

Parallel Circuits.—In a direct-current circuit consisting of a number of parallel branches, the voltage impressed is the same on all branches and the total current supplied to the circuit is equal to the sum of the currents in the different parts. In an alternating current parallel circuit the same relation holds provided the sum of the component currents is taken vectorially.

— **Diagram** for a Circuit with Parallel Branches —

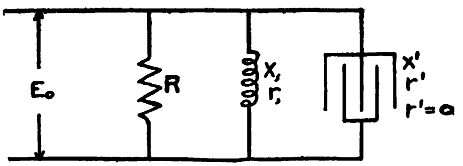


Fig. 50.

If the parallel branches of an alternating current circuit contain self-induction and capacity, the currents in these branches may be greater than the current supplied to the entire circuit from the mains.

In Fig. 51 E_o is the impressed voltage and I_o the current supplied to the entire circuit. I_o is the vector sum of the current in in the resistance, I_r, the current in the reactance coil, I_{xr}, and the current in the condenser $I_{x'}$.

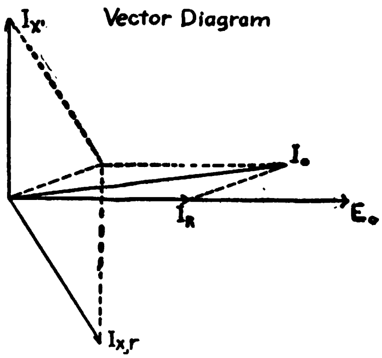


Fig. 51.

When the wattless components of the currents taken by the condenser and reactance coil are equal, the circuit is said to be in resonance.

It can easily be seen from the diagram that the current in the capacity or in the reactance branch may be greater than the current supplied to the entire circuit from the mains.

If the parallel branches should contain resistance, capacity, and self-induction, the current in each branch would be found as indicated under series circuits. The vector sum of these currents would then be the total current supplied from the mains.

Test.—Before performing this experiment read what is given under Wattmeters. (c. f. page 7.)

Apparatus:—A resistance of about 40 ohms and five amperes carrying capacity; two variable reactance coils each having a maximum reactance of about 40 ohms and very low resistance; four boxes of condensers each box containing about 15 microfarads; suitable wattmeters, ammeters, and voltmeters.

Each box of condensers is divided into five sections which may be connected in parallel by small switches mounted on the box.

When a section of condenser is disconnected, the small switch disconnecting it should be placed in the position marked discharge. If this precaution is not taken severe shocks may be received from what are apparently dead sections. The total capacity reactance of all four boxes when connected in parallel is about 45 ohms. The resistance is very nearly zero.

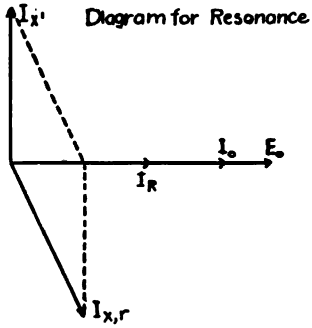


Fig. 52.

Series Circuits.—Make up a series circuit of resistance, capacity and reactance, using the two reactance coils in series and the four condenser boxes in parallel. The circuit should be protected by six-ampere fuses and should be connected by a suitable switch to the 115-volt 60 cycle laboratory mains.

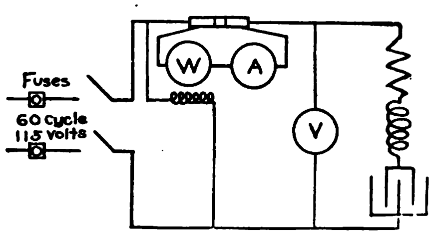


Fig. 53.

A 3_a ammeter, a 3_a - 150_v wattmeter and a 150_v voltmeter should be connected so as to measure the current, total power, and the total voltage of the circuit. If more voltmeters are available connect one of 300 volts capacity about the condenser and one about the reactance. It will also be convenient to have a voltmeter around the resistance. Probably one voltmeter will have to be used in place of these three. The proper connections are shown in Fig. 53.

The resistance in series with the potential coil of the wattmeter will be contained in the base of the instrument. The voltmeters around the resistance, reactance coil and condenser are not shown.

1. Place all the switches on the condenser boxes in the discharge position, set the reactance coils for maximum reactance, (iron cores down) then close the main switch. No current should flow. Now close the switches on the condenser boxes one at a time and note the effect on the current. Continue closing the switches until the voltage about the condenser and reactance coils are approximately equal. Since the resistance of the reactance coils is very small resonance will be reached approximately when the voltage drops about the condenser and the reactance coils are equal. These drops may be made exactly alike by adjusting the reactance coils. The voltage about both the condenser and reactance coil should now be considerably greater than the voltage of the mains. Read all instruments.

2. Reduce the reactance in the circuit by raising the core of one of the reactance coils. Again read the instruments.

3. Open the main switch and cut out the reactance coil. Get a set of readings with this out and also with the condenser taken out but with the reactance in circuit.

The power factor under the different conditions may be calculated by W_o/E_oI_o where the letters represent the readings of the instruments in the main line. If the instruments are connected as shown the reading of the wattmeter should have subtracted from it the power consumed by its current coil $I_o^2r_w$, the power taken by the ammeter $I_o^2r_a$, and the power taken by the voltmeters v^2/r_v. When r_w, r_a, and r_v are the resistances of the wattmeter current coil, the ammeter, and the voltmeter respectively.

From the data obtained draw the vector diagrams for the four different conditions. These can best be constructed as follows:

Refering to Fig. 54 draw a horizontal line OI_o to represent the current. Use the scale of one ampere to 2 1/2 inches. This will give a good decimal scale if the ordinary plotting paper divided into twentieths of an inch is used for the diagrams.

The voltage required to force the current through the resistance will be in phase with the current. Lay off a distance OE_r along the current line equal to this voltage as measured. Use a scale of 100 volts to 2 1/2 inches.

The current in the condenser will lead the impressed voltage by 90° In other words the voltage will lag 90° behind the current. Measure lag in a clockwise direction and lay a distance OE_c equal to the condenser voltage, lagging 90° behind the current.

The vector sum of $O\ E_r$, $O\ E_c$ and the voltage around the reactance coils must be equal to the impressed voltage E_o.

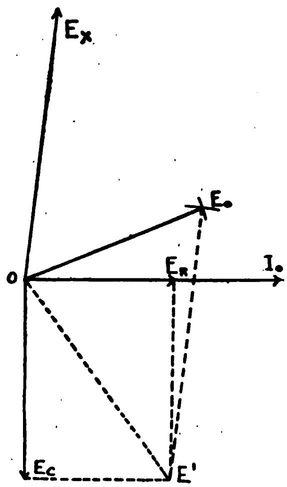


Fig. 54.

Find the resultant of $O\ E_r$ and $O\ E_c$ by completing the parallelogram $E_c\ OE_r\ E^1$. With O as a center and a radius equal to the voltage, E_o, impressed on the entire circuit, swing an arc. Also swing another arc with E^1 as a centre and a radius equal to the voltage, E_x, about the reactance coils. A line joining O with the intersection of these two arcs will give the direction and magnitude of the impressed voltage E_o.

To complete the diagram draw a line OE_x upward from O equal and parallel to the dotted line E^1E_o. This line, $O\ E_x$, represents in phase and magnitude the voltage across the reactance coils.

Parallel Circuits.—Make up a circuit with the resistance, reactance coils, and condenser in parallel. Place the four condenser boxes in parallel with one another and the two reactance coils in series. A short circuit block should be placed in each branch so that a 3-ampere ammeter may be inserted. A 5-ampere 150-volt wattmeter; a 5-ampere ammeter and a 150-volt voltmeter are connected so as to measure the watts, current and voltage supplied to the entire circuit. If a sufficient number of ammeters are available, of three ampere range, one can be put in each branch of the divided circuit, if not one ammeter will have to be changed from one branch to another.

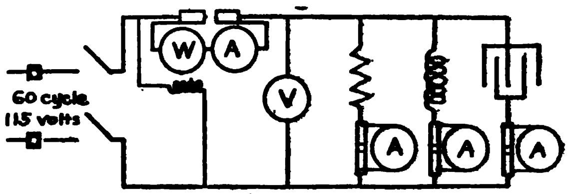


Fig. 55.

The proper connections are shown in Fig. 55.

Place all the condenser switches in the position marked discharge and set the cores of the reactance coils for maximum reactance, then close the main switch.

1. Connect the condenser sections one by one until the ammeter in the condenser circuit reads approximately two amperes. Notice the decrease in the current indicated by the main line ammeter. When this has been done adjust the inductance of the reactance coils until the current taken by them is equal to the condenser current. As this is done watch the main line ammeter. Resonance has now been approximately attained since the resistance of the reactance coils is very low. Read all instruments and record the current in each branch of the circuit.

Since the currents taken by the condenser and reactance coils are equal and about 180° apart in phase, the current coming through the main line ammeter to supply these is very small. If there were no losses in either the condenser or the reactance coils and the current taken by them were equal, the current supplied to both together from the line would be zero.

2. Open the circuit of the 40 ohm resistance and again take readings of all instruments. Compare the line current with the current taken by the condenser and reactance coils.

3. Put back the resistance and open the circuit of the condensers or the reactance coils and take readings. If the circuit of the reactance coils is opened the line current will lead the impressed voltage, if, however, the condenser circuit is opened the current will lag.

4. Put back the condenser or reactance coil and destroy the condition of resonance by screwing down the cores of the reactance coils. Record the readings of all instruments.

Draw vector diagrams for the above four cases of parallel circuits using scales as large as convenient for current and voltage.

Referring to Fig. 56 lay off a horizontal line equal to the impressed voltage E_o. The current in the resistance will be in phase with E_o. Lay off this current OI_R to scale along E_o. The condenser current, I_c, leads the voltage E_o by 90° and should be drawn vertically upward from OE_o. Find the vector sum of OI_c, and OI_R by constructing the parallelogram $I_R O I_c I'$. Then the sum of OI' and the current in the reactance must be equal to the current, I_o, supplied by the line. With I' as a centre and with a radius equal to the current in the reactance coils swing an arc. Swing another arc with O as a centre and with the line current I_o as a radius. A line joining O and the intersection of these two arcs will represent the line current in phase and magnitude. To complete the diagram draw the current in the reactance coils OI_x downward from O parallel to the line $I'I_o$.

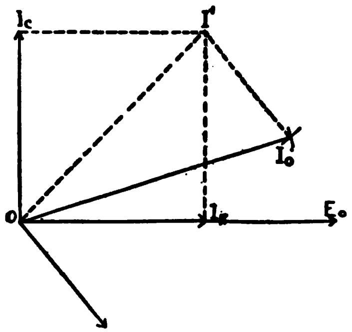


Fig. 56.

The cosine of the angle I_oOE_o is the power factor of the entire circuit and should, if the instruments are correct and the diagram is carefully drawn, be equal to the power factor of the circuit as given W/I_oE_o.

XVIII

POWER MEASUREMENTS IN THREE-PHASE CIRCUITS.

This experiment is to illustrate the use of the two-wattmeter and three-wattmeter methods for measuring power in three-phase circuits, as well as to show the relative readings of the wattmeters in the two-wattmeter method for varying power factors. Either the two-wattmeter or three-wattmeter method will give the true power in a three-phase circuit whether the load is balanced or not, provided, in the case of the two-wattmeter method, there is no neutral connection between the source of power and the load. Balanced loads will be used in this experiment since the power-factor of a three-phase system is meaningless unless the system is balanced.

The load will consist of three impedance coils taking 25 amperes at 200 volts, three impedance coils taking 15 amperes at 200 volts, and three variable non-inductive resistances. The resistances will be delta-connected. The impedance coils will be con-

nected in either △ or Y according to the amount of wattless current desired. Power will be taken from the 230-volt 60 cycle laboratory mains.

Five wattmeters, three ammeters and one voltmeter will be required. The current range of all the wattmeters and ammeters should be fifty amperes. The wattmeters for the three-wattmeter method will have $\frac{230}{\sqrt{3}} = 133$ volts impressed upon their potential coils. They should have a voltage range of about 150 volts. The other two wattmeters and the voltmeter will have 230 volts impressed on them. They should have a voltage range of 300 volts.

Read the directions given for the three and two-wattmeter methods (pages 11, 12) then make the connections for the experiment according to Fig. 57.

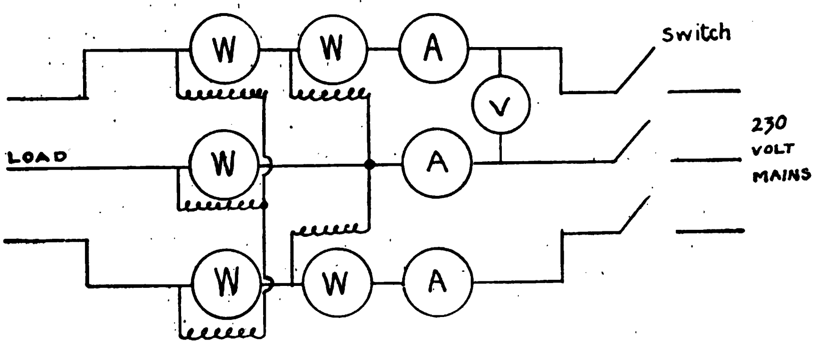


Fig. 57.

Connect the three 25-ampere impedance coils in △ across the line, close the switch and read all instruments. The ammeters should indicate approximately 50 amperes. If the wattmeters used for the two-wattmeter method have been properly connected, one of them will deflect backwards against the stop indicating a power-factor of less than fifty percent. Reverse the connections of the current coil of this instrument in order to make it deflect up the scale. Call its readings negative until its current coil connections again have to be reversed in order to make it indicate.

Replace the 25-ampere impedances by the three 15-ampere coils and connect the three non-inductive resistances in △ across the line. Close the main switch and adjust the non-inductive resistances until the ammeters again have the former readings. Read all the instruments. In this case the power-factor will be higher than with only inductance in circuit, and the deflections of the needles of the wattmeters used for the two-wattmeter method should be more nearly alike.

Change the connections of the 15-ampere impedances from △ to Y, and repeat the experiment. Finally remove the impedances entirely. Again adjust the current and read the instruments.

During the experiment note the behaviour of the wattmeters used for the two methods of measuring power. The sum of the readings of the wattmeters used for the three-wattmeter method should be the same as the algebraic sum of the readings of the wattmeters used for the two-wattmeter method. There may, however, be a slight disagreement between the two sums due to calibration errors of the instruments.

From the readings obtained, calculate the power-factors for the four different loads, and plot the ratio of the readings of the wattmeters used for the two-wattmeter method against the corresponding power-factors.

XIX

SINGLE-PHASE INDUCTION MOTOR.

The working parts of the characteristic curves of an induction motor whether it be single-phase or polyphase, much resemble those of a direct current shunt motor. The two types of motors are, therefore adapted to similar classes of work.

Single-phase induction motors are constructed in much the same way as polyphase motors except that their stators have single-phase windings. The action of the two motors when running is very similar, but while the polyphase motor is self starting a single-phase motor is not, since its torque, when at rest, is zero.

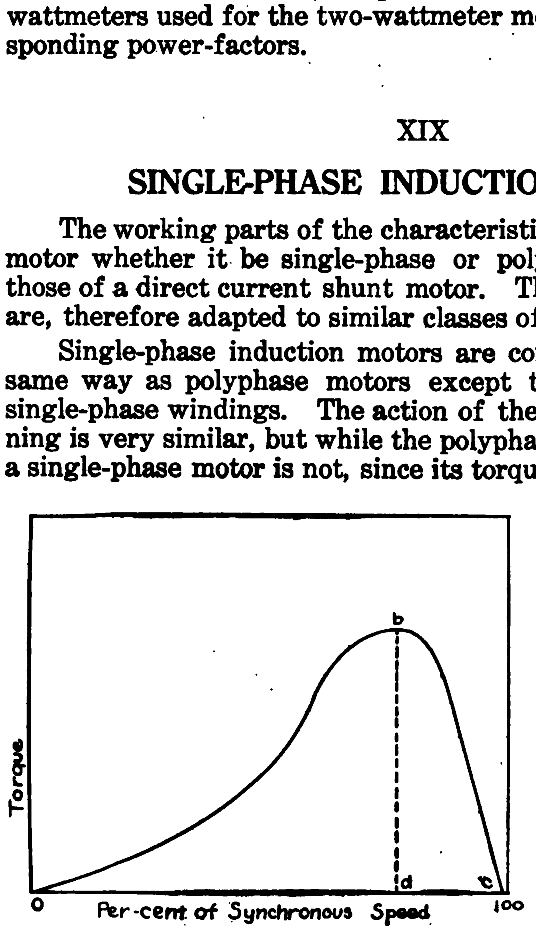


Fig. 56.

The synchronous speed of any type of induction motor is given by the frequency in cycles per minute divided by the number of pairs of poles on the motor independent of the number of phases. This is the speed which is often given on the name plate, the actual speed under load will be from three to ten per cent less than this according to the size and type of motor. The difference between the actual speed and the synchronous speed is the slip. Slip should be expressed in per cent of synchronous speed.

The complete speed torque curve of a single-phase induction motor is shown in Fig. 56.

The torque is zero at standstill and again is zero at a speed which is slightly less than synchronous speed. The working portion of the speed-torque curve is bc. The portion ob of the curve represents an unstable condition, since any decrease in speed such as would be produced by an increase in load, will cause a decrease in the torque and very quickly bring the motor to rest. If, on the other hand, the motor is running on the part of the curve bc, a decrease in speed will produce an increase in torque and enable the motor to carry more load.

Since the torque of a single-phase induction motor is zero at rest, some auxiliary device is necessary for starting and bringing it up to a speed such that the torque developed by the motor is sufficient to run it up on the working part bc of the speed-torque curve. It is in this starting device that the essential difference between different makes of single phase induction motors exists.

If an induction motor becomes overloaded while running so that its speed falls below d, it will quickly come to rest. When this "break down" point, as it is called, is reached, there will be a rapid increase in current which will cause the motor to be much overheated and may even burn out the winding unless the circuit is broken. The current under the conditions of breakdown may easily rise to three or four times the full-load value.

Test:—Inspect the motor to be used and determine the method of starting it. The motor will be provided with some form of friction brake or arranged as a dynamometer.

Connect the motor according to Fig. 59, being sure to follow the directions given for the connection of the wattmeter. (Page 7.)

R is the extension coil for the wattmeter provided one is needed.

In estimating the sizes of instruments required the efficiency may be assumed to be about the same as the efficiency of a shunt motor of corresponding size. The size of the ammeter and current capacity of the current coil of the wattmeter may be calculated by finding the full load volt-amperes of the motor and dividing these by the rated voltage. The volt-amperes are found by dividing the output by the efficiency and power factor. The full load power factor, as an approximation, may be assumed equal to the efficiency at full load. The current range of the instruments obtained in this way should be increased to allow for about 25% overload. The voltage range of the wattmeter should be at least equal to the rated voltage of the motor.

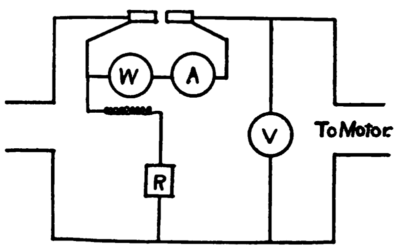


Fig. 59.

The speed should be obtained by subtracting the slip in revolutions from the synchronous speed calculated from the frequency

of the circuit as read on a frequency meter and the number of motor poles. If no method is provided for counting slip, speed must be obtained directly.

The simplest way of obtaining the slip directly is by means of a stroboscopic disc illuminated by an arc light which is operated from the same circuit as the motor. A disc having alternate black and white sectors, the number of black sectors being equal to the number of poles on the motor, is attached to the motor shaft and illuminated by an arc light which is operated from the same circuit as the motor so that the current supplied to the arc and to the motor have the same frequency.

The light from an alternating arc is not steady but fluctuates, being a maximum for each maximum of the current wave. Suppose the motor has six poles: if it were to run at synchronous speed it would make one revolution in the time of three complete cycles or six alternations. In this time the light from the arc would have six maxima. Also suppose that when the light is a maximum one of the white sectors of the stroboscopic disc is at the top, it would at that instant be illuminated. One alternation later, the light will again be a maximum. In this time the disc will have made one sixth of a revolution so that the next white sector will now be at the top. If the motor were to continue to run at synchronous speed, every time the light from the arc was a maximum a white sector would be at the top and the disc would appear to be at rest.

If the motor runs at less than sychronous speed, the white sectors will not have time between two successive maxima of the arc to move forward to the position occupied by the next preceding sector. Under these conditions, the sectored disc will appear to move slowly backward and apparently make one revolution in the time required for the motor armature to fall one revolution behind its synchronous speed. If the apparent speed of revolution of the disc is counted and the frequency of the circuit measured, the actual speed of the motor may be determined accurately. If p, f, and n be the number of pairs of poles on the motor, the frequency of the circuit, and the apparent speed of revolution of the disc in rev. per min., the actual motor speed will be $60\ f/p - n$.

Having wired up the motor, short circuit the ammeter and current coil of the wattmeter and bring the motor up to speed. There should be no load on the motor while starting. Carefully remove the short circuit from the wattmeter. If it reads backwards, short circuit again and reverse its current-coil connections.

Increase the load to about 25% overload, then holding the load constant by the brake count the apparent speed of the stroboscopic disc. Also record the readings of all instruments including the frequency meter. Decrease the load slightly and repeat. Proceed

in this way, taking readings about every eighth of full load, until zero load is reached.

From the data obtained plot curves of efficiency, torque, power factor, current and slip, all with horse-power output as abscissae.

Note:—As any single phase motor will take a considerable current at low power-factor while starting, do not start the motor any more often than necessary.

XX

THREE-PHASE INDUCTION MOTOR LOAD CHARACTERISTICS.

With the exception of the speed-torque curve, the characteristic curves of a polyphase induction motor do not differ essentially from those of a single-phase induction motor. The speed-torque curves of the two types of motors, however, differ materially at their two ends especially at the end corresponding to rest or 100% slip. While the torque of a single-phase induction motor is zero at rest, the torque of the polyphase motor has a definite positive value, depending in magnitude upon the design of the motor. The difference between the upper ends of the curves is of no great importance. The difference is, however, in the speed at which zero torque is reached. In the case of the single-phase motor it is slightly below synchronous speed.

Since the torque of polyphase motors is not zero at rest or 100% slip, polyphase induction motors are self-starting under light load or no load and may even be made self-starting under load if designed for that purpose.

The speed-torque curve of a polyphase motor is shown in Fig. 60. The motor operates on the part *bc* of the curve. The part *ab* representing, as in the case of the single-phase motor, an unstable condition. The ordinate *da* is the torque at rest. If this is greater than the torque necessary to overcome the friction of the motor and the load, the motor will speed until a condition of stability is reached on the part *be* of the curve. The position of the point *b* of maximum torque with respect to speed depends upon the resistance in the rotor circuit. Increasing

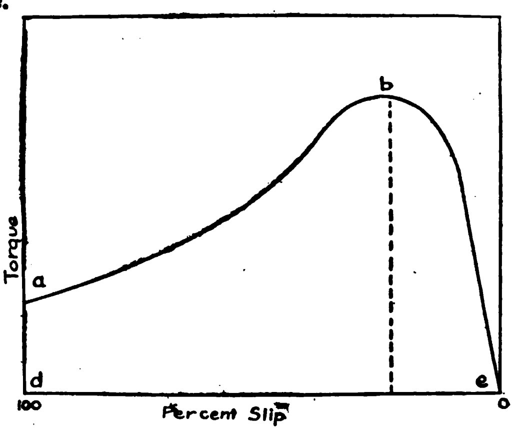


Fig. 60.

the resistance moves the point b to the left; decreasing the resistance moves b to the right. By adding the proper amount of resistance to the rotor circuit, it is possible to make the maximum torque occur at starting. This added resistance, if left in, of course, decreases the efficiency of the motor and in addition makes the speed regulation very poor. The effect of adding increasing amounts of resistance to the rotor circuit is shown in Fig. 61.

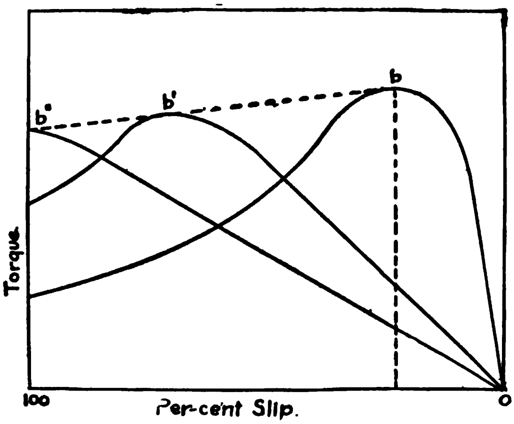


Fig. 61.

Since the speed regulation of the motor depends upon the slope of that portion of the curve between the point of maximum torque and synchronous speed, it is obvious that besides decreasing the efficiency, the addition of resistance to the rotor of an induction motor makes the speed regulation poor. The effect is much the same as that produced by adding resistance to the armature circuit of a d.-c. shunt motor.

Polyphase induction motors which are to be started under heavy load have their rotors wound and connected in Y so that resistance may be inserted while starting. This resistance, if used solely for starting, should be cut out when the motor is up to speed. In this case it is sometimes placed in the armature of the motor and arranged so that it may be thrown out by hand after the motor has been started. If the resistance is to be used for varying the speed of the motor, the three terminals of the Y-connected rotor must be brought out to three slip rings so that the resistance may be placed external to the armature for it is impossible otherwise to provide sufficient radiating surface to dissipate the heat developed in the resistance.

When the motors do not have to start any very great load and close speed regulation is required, they should have squirrel cage armatures and should be started on low voltage which is usually obtained by the use of a compensator.

Test:—Examine the motor assigned for this experiment and note the rating given on the name plate. Determine by inspection the type of rotor used and the method by which the notor is to be started.

A friction brake will be used for applying load, and an arc and stroboscopic disc or slip meter for determining the slip. (See notes on Single Phase Induction Motor.)

Read what is given under "Measurement of Power in Three Phase Circuits" (p. 11,) then connect the motor according to Fig. 62, using the two-wattmeter method for measuring the power input. Assumptions similar to those made in the experiment on the Single-phase Induction Motor may be made in regard to the power-factor and efficiency for estimating the sizes of instruments required. Short circuit blocks, not shown in the figure, should be used to protect the current coils of the instruments from injury. F is a frequency meter.

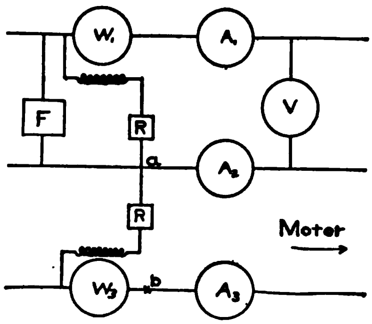


Fig. 62.

Having made the proper connections, short-circuit all current coils of the instruments and bring the motor up to speed. If the motor has self-contained armature resistance, be sure to cut this out as soon as the motor has speeded up. Put about 25% overload on the motor and allow it to run for ten or fifteen minutes, then record the readings of the two wattmeters, the three ammeters, the voltmeter, the frequency meter, the balance reading and the slip. If the voltage of the circuit is not exactly balanced, record the voltage between three pairs of lines. Do not fail to record the proper sign, plus or minus, with each wattmeter reading. Decrease the load slightly and take another set of readings, Proceed in this way until zero load is reached, then shut down the motor and get the zero reading of the brake.

From the results obtained plot the following curves:—Efficiency and output, torque and output, average line current and output, speed and output, and power-factor and output. In the report on this experiment, compare the characteristic curves of this motor with those of a shunt motor, making all proper allowances for differences caused by the curves being for motors of different sizes.

THREE-PHASE INDUCTION MOTOR SPEED-TORQUE CURVES.

This test is on a Westinghouse three-phase induction motor, Type F, 3.5 h. p., 440 volts, 60 cycles, 6 poles with variable speed controller. The variable speed is obtained by the insertion of resistance in the rotor circuit which is also wound three-phase. Before proceeding with this experiment, read what is given under "Measurement of Power in Three-Phase Circuits" and under the "Three-Phase Induction Motor."

The experiment will consist of obtaining the speed-torque curves for three positions of the controller, viz: the positions of highest and lowest speed and one intermediate speed; and the efficiency and power-factor for full load at the highest speed.

The motor is permanently connected with its controller to the laboratory mains, but gaps are left in each main for the insertion of instruments for measuring the input, which is to be obtained by the three-wattmeter method. The proper connections for the instruments are shown in Fig. 63.

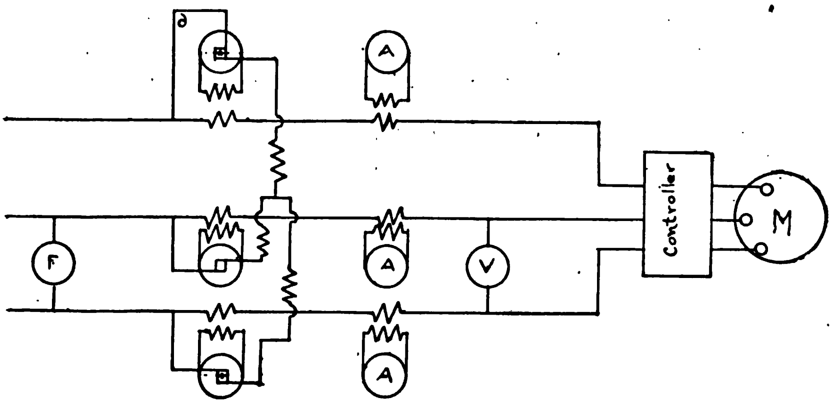


Fig. 63.

The ammeters and the current coils of the wattmeters are built for five amperes, but are provided with current transformers by means of which that range may be increased to 20 or 60 amperes, according to the transformer connections used.

The current transformers are nothing more than small transformers designed with very small iron losses. They are connected with one coil in the line and the other to the ammeter or wattmeter as the case may be. The currents in the two coils are inversely as the number of turns, so that by varying the ratio of turns in the coils, the same ammeter and wattmeter may be made to read full scale deflection for different line currents. Multiplying factors must be applied to the readings of instruments. (See the notice on the instrument board).

The output of the motor is measured by a friction brake. The speed is obtained from a speedometer which must be calibrated.

Test:—After the instruments have been properly connected, loosen the brake, short-circuit the ammeters and wattmeters, and start the motor by slowly turning the handle on the controller in a right-handed direction.

If a 440 volt motor is used, be very careful not to come in contact with the live terminals, as there will be a maximum voltage between lines of 620 volts. In taking out the short-circuit plugs to read the instruments, be sure to touch only one plug at a time and to keep out of contact with any metal while so doing.

With the controller in the position for the highest speed, gradually load the motor, taking readings of the speedometer and the balance. Readings should be made at five or six points between zero load and about 1.25 normal full-load torque, allowing for the zero reading of the brake. At about full-load take all readings necessary for calculating efficiency and power-factor. Throw off the load, set the controller in the mid-position, and take another set of readings of the speedometer and balance. Repeat with the controller in the position for minimum speed. Do not carry the balance reading much above the maximum value used on the first run. Stop the motor and disconnect any temporary wiring which was used.

From the above readings, calculate the speeds and torques and plot the results with % of synchronous speed as abscissae and torques as ordinates. Calculate also the power-factor and efficiency for full load at the maximum speed.

XXII

REGULATION OF AN ALTERNATOR BY THE SYNCHRONOUS IMPEDANCE METHOD.

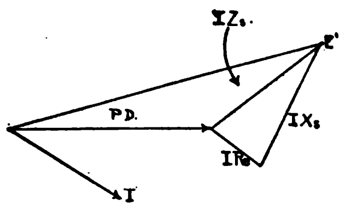


Fig. 64.

The synchronous impedance method for determining the regulation of an alternator is valuable in cases where, due to the size of the machine or other reasons, it is impossible to fully load the alternator. The regulation given by this method is in general worse than that shown by the actual performance of the machine. The alternator diagram is shown in Fig. 64. PD is the terminal voltage, R_eI is the resistance drop in the armature and is in phase with the armature current I, which in the above diagram is shown lagging. IX_s is the electromotive force which is necessary to overcome the e.m.f. due to the synchronous reactance X_s. The synchronous reactive e.m.f. is 90° behind the current. The e.m.f. which must be applied to overcome this is equal and opposite to it, i.e., 180° ahead of it or 90° ahead of the current as shown in Figure 64. The vector sum of PD, R_eI and IX_s will be the e.m.f., E', which is necessary to produce a terminal potential PD. E' is the e.m.f. the machine will have if the load is thrown off, i.e., it is the e.m.f. produced by the field current at the terminals of the machine at no load. In other words, it is the open-circuit potential corresponding to the field current which produced the potential difference PD under load.

IZ_s, in the diagram is the e.m.f. necessary to overcome the synchronous impedance of the armature. Since IR_e and IX_s are at right angles—

$$IZ_s = \sqrt{(IR_e)^2 + (IX_s)^2}$$

and—

$$Z_s{}^* = \sqrt{R_e^2 + X_s^2} \quad . \ . \ . \ . \ . \ . \quad (1)$$

If the generator be short-circuited P D will become zero and the diagram will collapse into Fig. 65.

*The synchronous reactance includes the effect of armature reaction as well as the true armature reactance.

*Note:—In most alternators, R_e is small compared with Zs so that Zs and Xs will be sensibly equal.

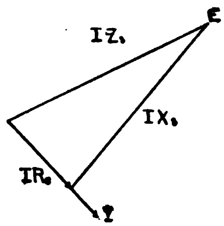


Fig. 65.

In this case E' is equal numerically to the synchronous impedance drop, IZ_s, in the armature. E' may be found by keeping the field current constant and throwing off the load, and E' will be the potential on open circuit.

$$E' = I\,Z_s$$
$$E_s = E'/I$$

If the resistance, R_e, of the armature be known, the synchronous reactance, X_s may be found from equation (1).

Due to the eddy current and hysteresis losses produced in the armature core and pole faces by the armature current, the apparent armature resistance of an alternator is greater than its ohmic resistance. This apparent resistance is called the effective resistance and for most alternators of the size used in this test is very nearly equal to 1.5 times the ohmic resistance. In the above equation R_e represents the effective resistance.

Regulation. — By the regulation of an alternator is meant the percentage increase in potential at the terminals produced by throwing off a full load. If PD is the rated full load potential and E′ is the potential measured when the load is thrown off, the regulation is

$$\frac{E' - P\,D}{P\,D}\,100 \quad . \; . \; . \; . \; . \; . \; . \quad (2)$$

If the rise in voltage is produced by throwing off a full non-inductive load the above expression gives what is called the inherent regulation.

The regulation or inherent regulation may readily be found from the alternator diagram provided X_s and R_e be known. The ordinary method of finding X_s and R_e will be described later.

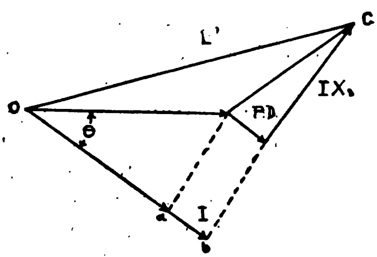


Fig. 66.

Fig. 66 represents the vector diagram of an alternator with the vectors $I\,R_e$ and IX_s exaggerated for the sake of clearness. Drop perpendiculars from the extremities of the vectors P D and $I\,R_e$ on the current line, then from the triangles thus formed.

$$E' = \sqrt{(ob)^2 + (bc)^2}$$
$$= \sqrt{(P\,D\cos\theta + I\,R_e)^2 + (P\,D\sin\theta + I\,X_s)^2}$$

When θ is the angle of lag of the current behind the terminal e.m.f., P D.

If the regulation is required for 0.8 power factor, $\cos\theta = 0.8$ and $\sin\theta = 0.6$. If the inherent regulation is desired, the angle of lag of the current behind the terminal e.m.f. is zero. Since $\cos\theta = 1$ and $\sin\theta = 0$, the expression for E′ reduces to

$$E' = \sqrt{(P\,D + I\,R_e)^2 + (IX_s)^2} \quad . \; . \; . \; . \; . \; . \quad (3)$$

Having found E′ the regulation is easily calculated by formula (2).

In order to determine the synchronous impedance of a machine two curves are necessary, i. e., the open-circuit characteristic and the short-circuit characteristic.

Open-circuit Characteristic.—The open-circuit characteristic or magnetization curve is obtained by running an alternator on open-circuit at its rated frequency and measuring its terminal potential as the field current is increased from zero to a maximum. The descending part of the curve is not necessary in this connection.

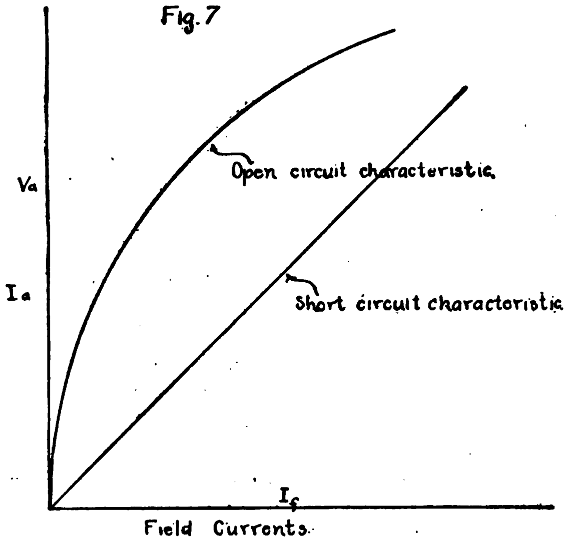


Fig. 67.

Short-circuit Characteristic.—The short-circuit characteristic of an alternator is taken by short-circuiting the machine through a low resistance ammeter or ammeters if the machine be polyphase and measuring the current in the armature for increasing field currents.

In taking data for the open-circuit characteristic, the field current must always be changed in the same sense, i. e.. it must not be carried above any desired value and then reduced. The open-circuit characteristic should be plotted with the voltage as ordinates and the field currents as abcissae. The armature current should be carried to a value corresponding to about a 50% overload. To avoid burning out the alternator the test should be begun with very small values of the field current. The field current which will give full load armature current on short-circuit will vary between 15% and 30% of the normal full-load value, depending upon the design of the machine.

The short-circuit characteristic should be plotted on the same sheet with the open-circuit characteristic, using field currents as abcissae and armature currents as ordinates. Two such curves are shown in Figure 67.

The value of the synchronous impedance is found by dividing the ordinates of the two curves for the same value of the field current. For example: For a field current of I_f the open voltage is V_a; the short-circuit current, I_a. The synchronous impedance is then

$$Z_s = V_a/I_a$$

The value of Z_s will vary according to the value of I_f used, decreasing slightly as the field current increases. That is due to the sat-

uration of the field. The value used in calculations should be for a field current as near full load as possible.

Test. — A small three-phase △ or Y- connected alternator will be used in this test.

The machine will be driven by a shunt motor, the speed of which can be controlled by a variable rheostat placed in the shunt field.

PROCEDURE

Open-Circuit Run. — Put several resistance boxes in series with the generator field and then connect it through a suitable switch to the 115-volt D.C. laboratory mains. A 10-ampere ammeter protected by a short-circuit block should be put in circuit. Connect a suitable voltmeter to any pair of the armature terminals of the alternator. The potential between all three pairs of terminals should be the same, so that one voltmeter will be sufficient.

Start the motor and bring the generator up to speed. The proper speed can be found by dividing the frequency by the number of the pairs of poles and multiplying by 60 to get the rev. per min. The final speed adjustment should be made very slowly by changing the motor field. After changing the field, wait a few seconds to give the motor time to slow down to the new speed before again changing the field. The speed must be held constant throughout the test. The generator connections for the above run are shown in Fig. 68.

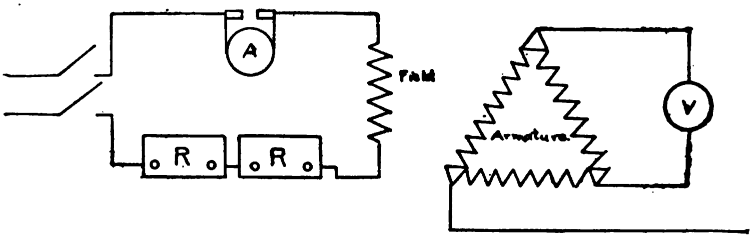


Fig. 68.

Having adjusted the speed read the voltmeter, then see that all the field resistance is in and close the field switch. Read the voltmeter and field current. Now gradually increase the field current to a maximum, taking readings of current and voltages for changes corresponding to about 15 volts. Then cut in all the resistance, open the field circuit, and shut down the motor.

Short-Circuit Run. — Short circuit each pair of armature leads through an ammeter having a maximum scale reading equal, if possible, to about $1\frac{1}{2}$ times the rated full load current of the alternator. The field circuit should be connected as before. (See Fig. 69.) The ammeters are connected in △ and hence will give the armature current directly.

Having made the proper connections, start the motor and bring the generator up to its proper speed. Put in all the resistance in the generator field, then cautiously close the generator field switch.

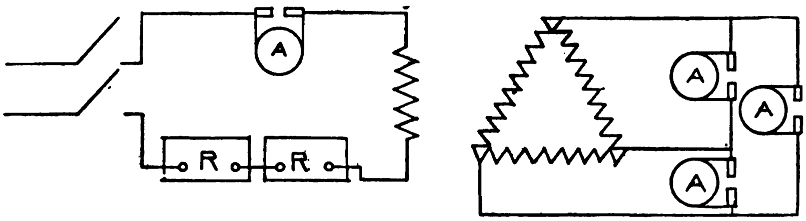


Fig. 69.

If the ammeters in the armature circuit go off the scale instantly open the switch. If everything is all right, the currents in the ammeters should be small.

Read these three ammeters and the ammeter in the field, then increase the field slightly and read again. Proceed in this way until the armature current is equal to about 1.5 the full rated value, i. e., 1.5/1.7 I where I is the rated full load current.* Readings should be taken for six or seven armature currents between zero and 1.5 its full load value. When this is done, open the generator field and shut down the motor.

The armature resistance per phase must now be measured. This is done by the drop of potential method which has been described earlier. Measure the resistance between each pair of armature leads and take the mean.

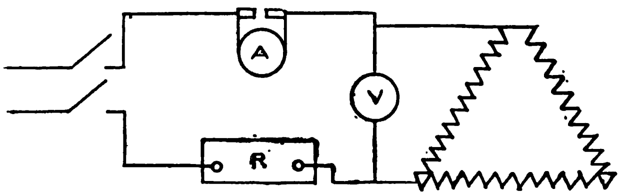


Fig. 70.

This resistance for a Δ connection will be the resistance of one armature branch in parallel with the other two in series. This multiplied by 3/2 will give the resistance per phase and this in turn multiplied by 1.5 will give the effective resistance per phase.

The proper connections for measuring the armature resistance are shown in Fig. 70.

* The armature current in a Δ machine is equal to the line current divided by the $\sqrt{3}$ or 1.7 approximately. The voltage of an armature is equal to the line voltage. In a Y-connected alternator, the armature current is the same as the line current, but the voltage of the armature per phase is the line voltage divided by 1.7. If a 15 K. W. machine should be used the ammeters connected as shown would read 38/1.7 or approximately 22 amperes for full load, since the full load current would be 38 amperes.

A voltmeter with a low-range scale will be needed at V. Be sure and try the high-range scale before changing to the low.

The resistance found from the voltmeter and ammeter readings will be that of r_1, in parallel with r_2, and r_3 in series.

This will be equal to

$$R = \frac{1}{\frac{1}{r_1} + \frac{1}{r_2 + r_3}}$$

$$= \frac{r_1 r_2 + r_2 r_3}{r_2 + r_3 + r_1}$$

If the resistances r_1, r_2, r_3, are all assumed to be equal

$$R = 2/3\ r_1$$

or

$$r_1 = 3/2\ R$$

The data from the open and short circuit runs should be plotted on the same sheet with field currents as abscissae, open circuit voltage as ordinates for one curve and mean armature current per phase (mean of the three ammeter readings) as ordinates for the other.

These two curves will be the open and the short-circuited characteristics of the generator.

Calculations.—The ratio of the ordinates of the two curves for any given field current will be the synchronous impedance corresponding to that field current. Since, as already stated, the synchronous impedance decreases somewhat as the saturation of the field is approached, the value Z_s used in calculating the regulation of the generator should be taken for as nearly normal conditions of field as possible. The best that generally can be done is to use the value of Z_s corresponding to the largest field current used in obtaining short-circuit characteristic.

Calculate this value, and find the value of the synchronous reactance from equation (1) using for R_e the value of the effective resistance per phase.

The inherent regulation can then be found from equations (3) and (2) using the normal voltage of the generator i.e., 230, for P D and the full load armature current for I. This latter will be the full load line current divided by $\sqrt{3}$.

Results Required.— Open-circuit and short-circuit characteristics; value of the synchronous impedance and reactance for the maximum field used in the short-circuit run; and inherent regulation at full load.

XXIII

REGULATION OF AN ALTERNATOR BY THE MAGNETO-MOTIVE FORCE METHOD.

The magneto-motive force method consists of two parts, viz: 1st. The determination of the amount of field current necessary to generate a voltage equal to that of the reactance drop plus the voltage generated by armature reaction flux. 2nd. The vector addition of this field current to that necessary to induce a voltage equal to the terminal voltage plus the IR drop in the armature.

The resultant of these two field currents is the impressed field and the voltage corresponding to this field on the open circuit curve is the no-load voltage.

The field current on the short-circuit curve represents the field necessary to equalize the armature reaction flux and in addition to generate a voltage equal to the impedance drop in the machine itself. This field may be assumed to balance the armature reaction and reactance effects, but neglects the armature resistance. The armature reaction being in phase with the current, this field will be 180° from the current.

The vector addition of the I R drop to the P D will give a fictitious induced voltage E^1. The field corresponding to E^1 on the magnetization curve is 90° ahead of it.

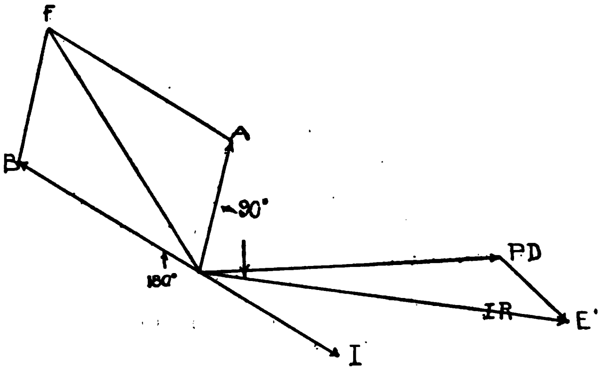


Fig. 71.

The value of the current and the angle between the current and P D must be known or assumed. R_e being known E^1 may be determined since I R_e is in phase with I. The field current A corresponding to E^1 on the magnetization curve may then be found. B is taken from the short-circuit run for a value of field current corresponding to I.

F is the vector sum of A and B, and the voltage corresponding to F is the open circuit voltage from which the regulation may be figured as in the synchronous impedance method.

It must be remembered that both of these methods are based on certain assumptions so that the results obtained may be in considerable error. One method may give better results than the

other on one machine and poorer results on another. As a general rule, the magneto-motive force method will give the better results although this depends to a considerable extent on the design of the generator considered.

Results Required.—Inherent regulation at full load and regulation on 80% P.F. lagging.

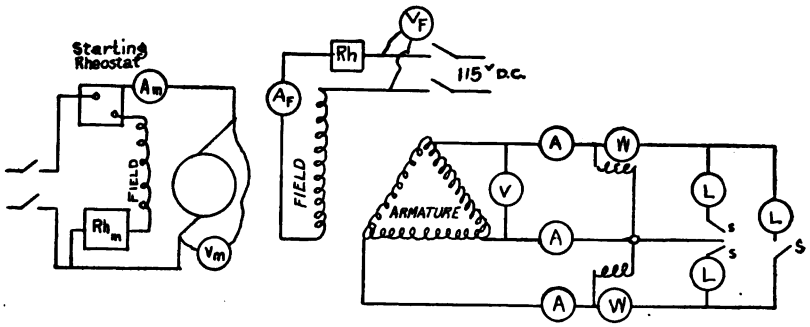
XXIV

MEASURED FULL LOAD EFFICIENCY, AND INHERENT REGULATION OF AN ALTERNATOR.

The machine which was used in the experiment on the determination of the regulation by the synchronous impedance and magneto-motive force methods will be used in this test.

The generator will be driven by a direct-current shunt motor.

The proper connections are shown in the following figure:



D. C. Motor. A. C. Generator.

Fig. 72.

An ammeter A_m is placed in the armature circuit of the motor and a voltmeter V_m is connected to its armature terminals. A resistance Rh_m for adjusting the motor speed is placed in the field of the motor.

The alternator is connected as shown with an ammeter A, in each line, and a suitable non-inductive load between each pair of terminals. A voltmeter V, also is connected between one pair of leads. The field of the generator, with its rheostat in series, is connected to the 115-volt d-c mains. An ammeter, A_F, and a voltmeter, V_F, are connected so that their product gives the loss in the generator field and its rheostat.

The two-wattmeter method will be used to measure the output of the generator.

The circles marked *W* in the figure represent the current coils of the two wattmeters, and the zigzag lines just outside the circles, represent the potential coils.

Procedure.— Short circuit all ammeters and wattmeters, and see that the switches connecting the resistance loads L, to the generator are open. Cut all the resistance out of the motor field, then close the switch connecting the motor to the mains, and bring the motor up to speed by means of its starting rheostat. Now adjust the speed of the motor by means of its field rheostat until the generator runs at its rated frequency, then close the generator field and bring the terminal potential of the generator up to its rated value.

Now gradually load the alternator at the same time keeping the frequency and potential of the generator constant, and at approximately their rated values. The load must be kept balanced.

When the ammeters register approximately full-load current, carefully adjust the frequency of the alternator and its voltage to exactly their rated values, at the same time holding the generator current constant at its rated value.

When this has been done, record the frequency of the generator and the speed of the motor, as well as the readings of all instruments. The sum of the two wattmeter readings will give the output of the generator armature.

The power factor of the load is given by

$$\frac{W_1 + W_2}{(A_1 + A_2 + A_3)\ \dfrac{V}{\sqrt{3}}} = \text{P.F.}$$

Where W_1 and W_2 represent the readings of the two wattmeters, and A_1, A_2, and A_3 the readings of the three ammeters, and V the reading of the voltmeter. If the load is balanced, the reading of the voltmeter should be the same between any pair of terminals.

The product of the motor armature current I_a, by the terminal voltage V_t, gives the input to the motor armature.

The loss in the generator field will be $I_f V_f$.

Having taken all the readings, gradually throw off the load, at the same time keeping the generator frequency constant by means of the rheostat in the motor field. Do not change the field of the generator. When the load is all off, read the potential at the terminals of the generator. If this be called E, and the potential when under full load be called PD

$$\frac{E - PD}{PD}$$

will be the regulation. Since in this case the load is non-inductive, the above expression will give the inherent regulation of the altertor.

To find the efficiency of the generator, it is necessary to find its input at full load. This can be found by subtracting from the input to the motor already found, the stray power and the I^2R loss in the motor armature.

The stray power is to be found by the method described in the experiment on stray power.

In order to do this, the motor must be shut down and its armature resistance measured. A suitable resistance is provided to put in series with the armature for this measurement. Having determined the armature resistance, calculate the armature potential of the motor when driving the generator under full load. This will be $V_t - I_a R_a = V_a$, where R_a is the value of the armature resistance found, and I_a the current in the motor armature when driving the generator fully loaded.

Take the belt off the motor and start the machine up idle, with a variable resistance inserted in the armature circuit. Now adjust the armature resistance and field resistance of the motor until it runs at the same speed, and has the same armature voltage that it had when driving the generator fully loaded. In making this adjustment it will be found convenient to adjust first the armature voltage by means of the armature rheostat and then the speed by means of the field rheostat. When the motor is running idle the armature voltage may be assumed equal to the terminal voltage. Read and record the speed, armature current, and terminal voltage. Call these latter I'_a and V'_T.

The stray power will be $I'_a V'_T - (I'_a)^2 R_a = S\,P$

This is the stray power corresponding to the condition of full load on the generator.

The input to the generator under full load neglecting belt loss will be
$$I_a V_T - S\,P - I_a^2 R_a = W\text{ input},$$
where I_a and V_T are the current in the motor armature and the voltage at the terminals of the armature, when driving the generator fully loaded.

If the belt loss be counted as one of the losses of the generator, the efficiency of the generator on full non-inductive load will be
$$\frac{W_1 + W_2}{W\text{ input} + I_F V_F}$$

Calculate the values of the following quantities and tabulate.

- Power-factor of load.
- S. P. of motor corresponding to full load conditions of generator.
- R_a = resistance of motor armature.
- Loss in generator field at full load.
- Inherent regulation of generator.
- Efficiency on full non-inductive load.
- A comparison of the measured and calculated inherent regulation.

XXV

TRANSFORMER EFFICIENCY AND REGULATION.

Since the efficiency of a transformer at full load will seldom be below 95% and may be as high as 98% in large sizes, it is important, especially in competitive tests, that efficiency determinations be made with considerable accuracy. Any method involving a direct measurement of the output and the input and taking their ratio is practically worthless, since any error made in the determination of either of these enters directly into the result i.e., the measured efficiency. Methods involving a direct determination of losses must be used. (See notes on Stray Power, page 31)

The measurement of the losses of a transformer is extremely easy. One of the simplest methods is the following.*

The losses of a transformer can be separated into copper losses and iron losses. The first of these is made up of the I^2R losses in the primary and the secondary circuits; the second includes the eddy current and hysteresis losses in the iron core. These latter are dependent upon the flux density in the iron core. (Flux density is the number of magnetic lines of force per unit area of the cross-section of the core.) The flux density is directly proportional to the induced voltage in the primary and secondary coils. This depends upon the voltage impressed on the transformer and varies but slightly with the load. Since this variation is small the core loss may be considered constant for any impressed voltage and frequency and independent of the load.

If the core loss and the resistance of the primary and secondary coils be measured, the efficiency at any load may be expressed as follows:

$$\frac{\text{Output}}{\text{Input}} = \frac{\text{Output}}{\text{Output} + \text{Losses}} = \frac{V_2 I_2}{V_2 I_2 + \text{core loss} + I_1^2 R_1 + I_2^2 R_2}$$

Where V_2 is the rated secondary voltage of the transformer and I_1 and I_2 are the primary and secondary currents, respectively, R_1 and R_2 are the primary and secondary resistances.

Example.—A certain 15 K.V.A. 10:1 transformer with a 200-volt secondary has the following constants:

$$R_1 = 4.0 \text{ ohms}$$
$$R_2 = 0.04 \text{ ohms}$$

The core loss with 200 volts on secondary or 2000 on primary is 300 watts.

The secondary current will be 15000/200 = 75 amperes.

The primary current will be 75 ÷ 10 = 7.5 amperes. This last is true when the no-load current is neglected. This can be done

* Throughout the test the high-tension side will be considered as the primary side.

without producing sensible error in the efficiency. Full load efficiency will be

$$\frac{15000}{15000 + 300 + 0.04(75)^2 + 4(7.5)^2} = 96.6\%$$

The efficiencies at other loads may be found by using values of the current corresponding to the load for which the efficiency is desired. For example, the half load I should be 75/2 = 37.5.

Measurement of the Core Loss.—The losses in a transformer are independent of the winding upon which the proper voltage is impressed but when measuring the core loss it is much more convenient and safer to supply the voltage to the secondary, or low-voltage side.

To determine the core loss, connect the secondary of the transformer through a switch to mains of a proper frequency and voltage. The primary circuit should be open and *its terminals placed so that there is no possibility of coming in contact with them.* If the switch connecting the secondary to the mains is now closed the magnetization of the core will be that for which the transformer is designed, and the energy supplied will be equal to the core loss plus a very small I^2R loss in the secondary which will be entirely negligible. If a wattmeter is placed in circuit, its reading will be equal to the core loss of the transformer. A voltmeter and an ammeter should also be placed in circuit. The ammeter will give the no-load current of the transformer, while the voltmeter will serve to show whether the proper potential is supplied to the transformer.

The connections are shown in Fig. 73.

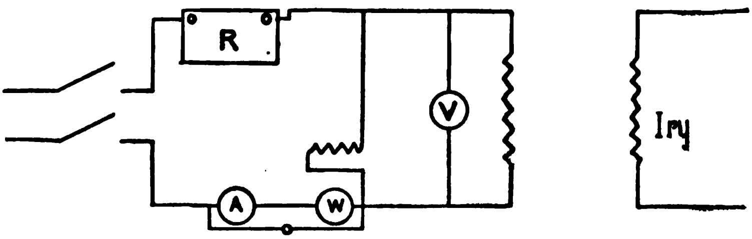


FIG. 73.

1 ry is the primary coil.

A is the ammeter.

W is the current coil of the wattmeter.

V is the voltmeter.

R is a variable resistance. (An auto-transformer is better for the voltage control and should be used if one is available.)

The size of a wattmeter is always determined by the apparent watts to be measured and never by the true watts. Therefore the wattmeter used for the connection shown above must have a

potential coil which will stand the rated voltage of the secondary of the transformer and a current coil which will carry the no-load current of the transformer. The no-load current of a transformer generally will be between three and five per cent. of the full load current.

Copper Losses:—The copper losses may be found from the resistances of the primary and secondary coils as already indicated. They may also be found by short-circuiting either the primary or the secondary coil of the transformer and applying sufficient voltage to the other side to force full load current through the coils. The better winding to short circuit depends upon the size of instruments and voltage supply available. The low pressure or secondary side is usually short-circuited. In a well-designed transformer the voltage required for this ought not to be over ten per cent. of the rated voltage of the primary and generally will be less.

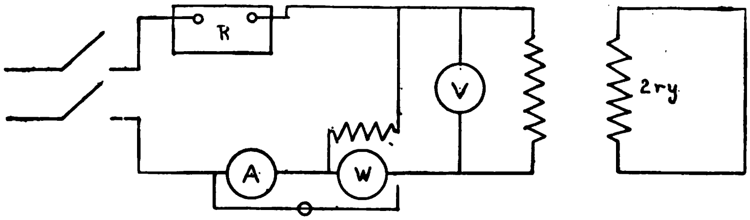


Fig. 74

The power supplied on short-circuit will be for the primary and secondary I^2R losses and a very small core loss which is negligible.

The proper connections for the short-circuit run are shown in Fig. 74. The same nomenclature is used as in the previous diagram.

The potential of the mains should not be more than ten per cent. of the rated primary potential of the transformer unless a sufficiently large resistance is employed at R.

The wattmeter should have a current coil which will carry the rated primary current of the transformer without over heating. It should have a potential coil for a voltage between five and ten per cent. of the rated primary voltage of the transformer.

Plenty of resistance should first be placed in R, then the switch connecting the transformer to the mains should be closed. If then R is adjusted so that full-load current is indicated by (A), the wattmeter will indicate the full-load copper loss, for the core loss with such a low impressed voltage will be negligible.

This copper loss W_c is equal to the total I^2R loss in the transformer. This varies as the square of the primary or secondary current in the transformer and will be equal to a fictitious resistance multiplied by the square of the primary or secondary current.

This resistance is called the equivalent resistance of the transformer and is referred to the primary or secondary side according as primary or secondary current is used in finding it. The two values of the equivalent resistance of a transformer will be to each other as the square of the ratio of transformation of the transformer.

R' (referred to primary) $= W_c/I_1^2$

R'' (referred to secondary) $= W_c/I_2^2$

$$\frac{R'}{R''} = \frac{\dfrac{W_c}{I^2_1}}{\dfrac{W_c}{I^2_2}} = \frac{I^2_2}{I^2_1} = a^2$$

where a is the ratio of transformation of the transformer.

The total copper loss for any load may be found by multiplying the equivalent resistance by the square of the current (primary or secondary according to the value of the equivalent resistance used) corresponding to the given load.

The potential V required to force full-load current through the transformer on short-circuit is used up in overcoming the impedance drop in the transformer, and is, therefore, numerically equal to the impedance Z of the transformer multiplied by the current I.

$$V = IZ$$
$$Z = V/I$$

Z as well as the equivalent resistance may be referred to either the primary or secondary side of the transformer. If the secondary is short-circuited, V will be the measured voltage on the primary side and

$$V_1 = I_1Z'$$

where I_1 is the current in the primary with the secondary short-circuited and Z' the impedance of the transformer referred to the primary side.

This impedance, Z', is the vector sum of the resistance R' (found from the short-circuit run) and the reactance X' referred to the primary side of the transformer.

These vectors are at right angles to each other. Therefore:—

$$Z' = \sqrt{X'^2 + R^2}$$

or

$$X' = \sqrt{Z'^2 - R'^2}$$

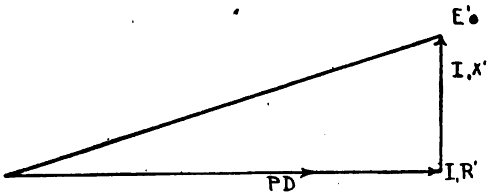


Fig. 75

With X' and R' known, the regulation of the transformer can be easily calculated from the simple transformer diagram. Fig. 75 represents the diagram for a non-inductive load.

In this case PD and I_1R are in phase since the load is non-in-

ductive. From the figure it follows that:—

$$E_0' = \sqrt{(PD + I_1R')^2 + (I_1X')^2}$$

The inherent regulation is given by:—

$$\frac{E_0' - PD}{PD}$$

Example.—Suppose that the value of X′ for the transformer used in the example on page 74 was found to be 16 ohms and that R′ was found from the short-circuit run to be 8 ohms. Assume that the transformer is used to step up the voltage and has a voltage impressed upon it such that its terminal voltage under a full non-inductive load is 2000 = PD. The full load primary (high voltage) current is 7.5 amperes.

$$E'_0 = \sqrt{(2000 + 7.5 \times 8)^2 + (7.5 \times 16)^2} = 2063$$

The inherent regulation is $\frac{2063 - 2000}{2000} = \frac{63}{2000} = 3.1$ per cent.

The same result would have been obtained if the value of X and R referred to the secondary side had been used. In this case, however, 200 would have seen used for PD and 75 for I.

Test:—This experiment will be performed on a 7-1/2 K.V.A. or a 5 K.V.A. 60-cycle transformer. The transformer may be connected for 10 to 1 ratio.

NOTE:—The high voltage terminals of the transformer to be tested are enclosed by a box which cannot be opened without breaking secondary circuit and making the transformer dead; but to avoid the possibility of any danger, the switch connecting the transformer to the mains must not be closed until the connections have been inspected and approved. This applies to the short-circuit run as well as to the open-circuit run.

It will be noticed that the low tension winding is in two sections which must first be connected in series i.e. so that the ampere-turns of the two coils at any instant tend to cause a flux in the same direction. To test for this condition connect the coils as shown in Fig. 76. Impress not more than the normal voltage upon either coil and measure the total voltage across the two. If no deflection of the voltmeter is obtained, connect b and d and measure voltage ac. For the proper connection the voltage across the two coils should equal twice that impressed on ab.

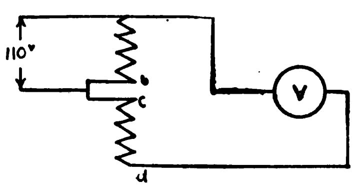


Fig. 76

First test for the proper connection of the two secondary windings. Then connect up as shown in Fig. 73 putting a resistance, or an auto-transformer, (not shown in the figure) in circuit so that the voltage may be adjusted. When the connections are properly made short-circuit the ammeter and wattmeter, and close the switch. Adjust the voltage to rated value and read all three instruments. The corrected wattmeter reading will be the core loss.

Disconnect the transformer and connect as shown in Figure 74, supplying voltage to the high voltage side. Use 230 volts on the mains. Reduce the voltage on the transformer to a minimum by means of rheostat or auto-transformer. Short-circuit the ammeter and wattmeter and close the main switch. Increase voltage until full load current flows in the primary, then read all instruments. This completes the test and gives all the data necessary for calculating the efficiency.

Results Required:—Full-load efficiency and inherent regulation on a full non-inductive load. Correction for instrument losses should be made as indicated under "Wattmeter" (pp 9 and 10.)

XXVI

CONSTANT-CURRENT TRANSFORMER

A small constant-current transformer with a low voltage primary will be used for this test. A sketch of this transformer is shown in Fig. 77. Either series incandescent lamps or resistance will be used for a load. *C* is the iron core, *PP* the primary coil, and *SS* the secondary coil. The secondary coil is movable and is hung from an arm (not shown) which is nearly counter-balanced.

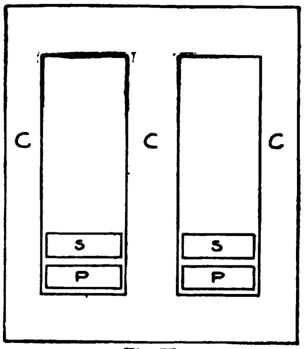


Fig. 77

The counter-weights are arranged so that when the transformer is delivering its maximum output the primary and secondary coils are in contact. Under these conditions the leakage reactance is small. Any increase in the secondary current due to the short-circuiting of the lamps forming the load will produce an increased repulsion between the coils and cause them to move apart. This increases the leakage reactance and cuts down the current. It is possible, by properly shaping the arm which carries the counter-weights, to have the transformer maintain automatically nearly constant current in the secondary circuit from full-load down to no-load.

Test:—The object of the experiment is to determine the characteristic curves and limits of regulation of the transformer when used on a non-inductive load consisting either of a bank of series incandescent lamps or non-inductive resistance.

The proper connections for the transformer are shown in Fig. 78.

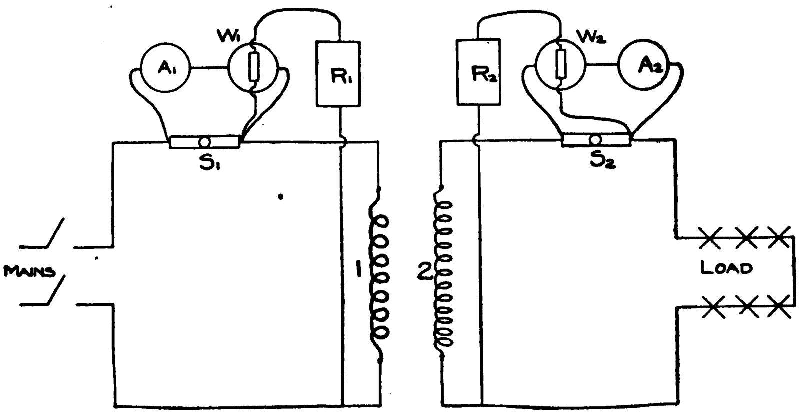


Fig. 78

The subscripts *1* and *2* refer to primary and secondary respectively. S_1 and S_2 are short-circuit block sfor the instruments, W_1

and W_2 are the wattmeters, A_1 and A_2 are the ammeters, and R_1 and R_2 are the extension coils for the wattmeter potential coils.

To avoid complication, the voltmeter is not shown in the diagram. One voltmeter will be used. This will be connected in such a way to a small switch that it may be thrown with suitable multipliers on to either the primary or secondary coils of the transformer. When connected to the secondary, its readings should be multiplied by four. Multiply by two for the primary voltage.

Wattmeter Connections:—In order to avoid injury to a wattmeter as well as false deflections due to static changes, the directions given on page 9 must be followed.*

Ask about the method of adjusting the load.

After having connected the transformer as shown in the diagram, have the connections examined. If they are correct, short-circuit the ammeters and wattmeters, raise the secondary coil to its highest position and close the main switch. Put a small load on the transformer, then carefully remove the short-circuit plugs from the instrument. If either of the wattmeters deflect backwards, immediately short-circuit it, shut down the transformer, and reverse the terminals of the current coil of the wattmeter.

Again raise the secondary coil to its highest position and close the main switch. Be sure the load is zero, then read all instruments. The secondary wattmeter will read zero, the primary wattmeter very nearly zero.

Now put a small load on the transformer—about two lamps if lamps are used—and again read all instruments. The instruments should be read as nearly as possible simultaneously. Continue in this way until the secondary of the transformer begins to float, i.e., to leave the top of the transformer core. Carefully note the readings of all instruments. This marks the beginning of automatic regulation. Continue loading the transformer, until the secondary coil seats. Note the readings of all instruments at this point. This is the other limit of regulation. Increase the load a little further, then after reading all instruments reduce the load to zero and shut down the transformer. This will complete the test. The curves to be plotted are: Efficiency and Output, Primary Power-Factor and Output, Secondary Current and Secondary Volts.**

$$\text{Efficiency} = \frac{\text{Watts output}}{\text{Watts input}}$$

$$\text{Power factor of primary} = \frac{\text{Primary watts}}{\text{Amperes} \times \text{volts}}$$

*A series circuit must never be broken. On the other hand, a constant potential must never be short-circuited. Lamps on a series circuit are cut out by short-circuiting.

** Care must be taken not to break the secondary circuit of this transformer while in operation as the voltage will rise to a dangerous value. Do not touch the secondary circuit while the transformer is operating.

XXVII

TRANSFORMER HEAT RUN AND EFFICIENCY TEST BY THE OPPOSITION METHOD.

In order to test a transformer for its rise in temperature under load, it is necessary to operate it under normal conditions of flux and current for sufficient length of time for it to reach its ultimate temperature. Although a transformer which is used for lighting purposes will seldom be run at a full load long enough to reach its final temperature, a knowledge of the final temperature is, nevertheless, important.

A run of eight hours will generally be sufficient except in the case of large transformers which are built for power purposes. A simple way of making a heat run on a transformer is to supply the proper voltage to the primary side and load the secondary with any suitable artificial load until it delivers full-load current. If a large transformer is to be tested by this method, the cost of the power consumed will be an important item.

Whenever two similar transformers are available, the following opposition method is economical of power and satisfactory. Data may easily be obtained during the test, from which the effiiciency under full load conditions may be calculated with accuracy. The rate at which the temperature rises may also be obtained.

For the opposition test of two transformers, the primaries or low pressure sides of the transformers are connected in parallel and power is supplied to them at their rated frequency and voltage. If the secondaries or high pressure sides are on open circuit, the power supplied to the primaries will be the core losses of the two transformers plus a negligible copper loss. If the secondaries are now connected in series and in opposition (like terminals together), no current will flow through them since their potentials at every instant will be equal and opposite. The conditions, in so far as the primaries are concerned, are unaltered by short-circuiting the secondaries, provided they are in opposition.

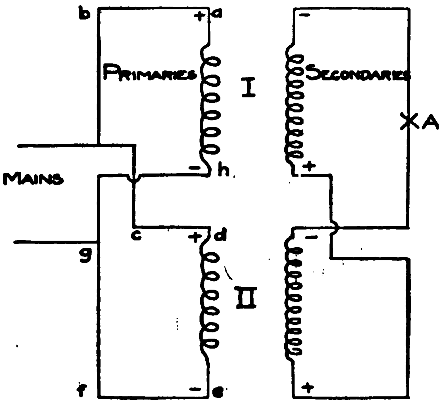


Fig. 79

I and II represent the two transformers respectively.

Fig. 79 shows diagramatically, the primaries of the two transformers in parallel with the secondaries in series and opposing.

The plus and minus signs indicate the voltage relations in the system at the instant when the upper ends of the primaries as shown in the figure, are positive.

The primary coils are in parallel since like terminals are connected together and to the same main. If the secondary circuit is followed through, it will be seen that the primary coils are in opposition.*

If at any point in the secondary circuit as, for example, *A*, an electro-motive force be produced such as to cause full load current in the secondary coils, full current will also be produced by induction in the primaries. This current in the primaries will not enter the external circuit but will simply circulate through the closed circuit, *a b c d e f g h*, formed by the primary coils. As far as the secondaries are concerned, the primaries are virtually short-circuited. It follows that the power supplied at *A* to maintain the full-load current in the transformers is the total copper loss of both transformers since the power supplied to any short-circuited transformer is, with the exception of a negligibly small core loss, all used up in this way.

The core loss can then be supplied through the primaries while the copper loss can be supplied through the secondaries by inserting the secondary of the third transformer in the secondary circuit at *A*, and raising the voltage impressed on this transformer until full-load current exists in the transformers under test. The circuit instead may be broken at *A* and connected to the mains through a suitable resistance, but the use of a third transformer is better.

The voltage at *A* which will produce the full-load current in the transformers under test is approximately equal to twice the impedance voltage of one transformer measured on the secondary side. This generally will not be over ten per cent of the rated voltage of one transformer.

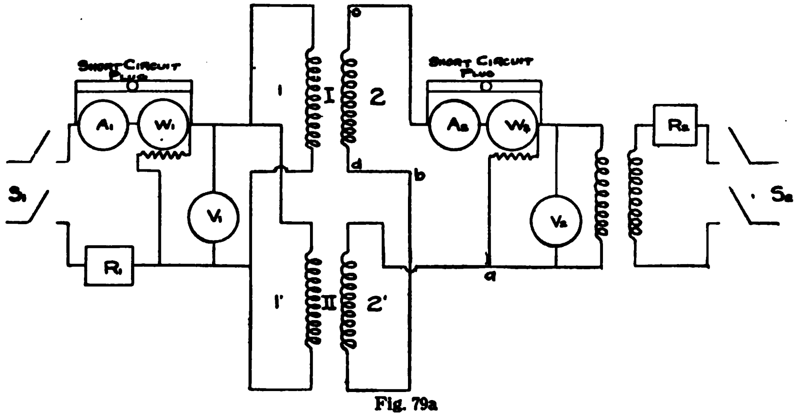


Fig. 79a

The complete connections for the opposition test of two transformers are shown in Figure 79a.

*The primaries, with respect to their own series circuit, are also in opposition.

Wattmeters, W_1 and W_2, give the core and copper losses, respectively, of both transformers. Ammeter A_1 indicates the sum of the no-load currents of the two transformers while A_2 shows the secondary load current carried by each of the transformers and serves to show when the conditions of full load have been attained. Voltmeter, V_2 gives twice the impedance voltage of a single transformer and also serves to show what voltage is being impressed on the potential coil w_2 of wattmeter W_2. Voltmeter V_1 is used to indicate whether the proper voltage is being applied to the transformers.

Wattmeter W_2 should have a current coil which will carry the rated current of the secondaries of the transformers while its potential coil should be for a voltage equal to twice the impedance voltage of the single transformer or from 8 to 10 per cent. of the secondary voltage of one transformer.

Wattmeter W_1 should have a potential coil for a voltage equal to the primary voltage of the transformers under test. Its current coil will have to carry twice the no-load current of one transformer or from 5 to 10 per cent of the full-load primary current of one transformer.

There are a number of ways of testing for opposition of the primaries. If a high range voltmeter is not available, the following method is simple and perfectly satisfactory.

To test for opposition, insert a variable resistance anywhere in the mains as at R. When this resistance is set for a maximum it should take only a small current.

With this same resistance in circuit, another test may be made by means of a voltmeter across the low-tension winding. If the connections are correct there will be a very small voltage drop across the resistance and, therefore, the voltmeter will read nearly line voltage. If the connections are not correct, the reading of the voltmeter will be very much less, as the voltage impressed will be equal to the IZ_e drop through the transformers and I is kept small by the line rheostat.

Another test may be may from the high tension side as follows:—Make all the connections as in Fig. 79a, then close S_2 leaving S_1 open. If the connections are correct, the low voltage side will be short-circuited with respect to the high side, and full-load current as indicated by A_2 will flow for a voltage of less than ten per cent of normal. The reading of the volmeter V_1 may also be used as an indication of correct connection in this last method. If the low-pressure coils are properly connected, there will be no voltage impressed on V_1 while if the connections are incorrect, the voltage impressed will equal the voltage on either of the high sides into the ratio of transformation.

If the switch S_1 now be closed and the resistance at R gradually reduced, the reading of ammeter A_2 should remain zero, provided the secondaries are in opposition since, in this case, the resultant potential in the secondary circuit will be zero. If, on the other hand, the secondaries are not in opposition there will be a resultant potential acting in their circuit when S_1 is closed and a current will be shown by A_2.

Test:—The secondaries of a third transformer are to be used as a *1:1* transformer to supply the copper losses of the transformers under test. Any transformer which will give a voltage equal to twice the impedance voltage of the two transformers under test and a current equal to the secondary current of one of these will answer.

As a matter of protection all the high voltage terminals of the transformers are placed in a box. The cover of this box is arranged to break all the low-voltage circuits of the transformers when it is opened and consequently make the high-voltage terminals dead. No wires must be brought out through the cover of the the box. The low-voltage coils of the transformers will be used as primaries.

Procedure:—Connect the transformers as shown in the diagram given on page 100 with a resistance frame inserted at R.

Care must be taken not to get the potential coil of wattmeter W_2 across high voltage. This will occur, if, by mistake the terminal a of the potential coil is connected to b. Such a connection will cause the instrument to be burned out instantly.

When the connections have been properly made and inspected, insert the maximum resistance in R, and close S_1. Carefully remove the short circuit from A_2. If the secondaries are in opposition, no current should flow as the resistance in R is reduced. If, however, they are not in opposition, a current will be indicated by A_2. If A_2 deflects, open S_1 and reverse the connections of one of the secondary coils, for example, interchange the points d and e.

When the proper connections for opposition of the secondaries have been found, close S_1 and gradually cut out the resistance in R until the rated voltage of the transformers under test is impressed on the primaries. This will be shown by the reading of V_1.

Now arrange R_1 for maximum resistance, and close S_2. Gradually decrease the resistance in R_2 until full-load current exists in the primaries. This condition will be shown by the reading of ammeter A_2.*

The transformers will now be carrying full-load current and will be fully excited and therefore, will be under the conditions of

* Full-load current will also flow in the secondaries.

full load. The only power supplied to the system, however, will be that for the core and the copper losses of the two transformers under test. The core and copper losses of the two transformers will be indicated on the wattmeters W_1 and W_2 respectively.

The transformers should be kept under the conditions of full load for a sufficient length of time for them to reach their final temperature. This generally will require in the neighborhood of eight hours. At the end of this time the transformers should be shut down and their temperature immediately measured.

The rise in temperature may be calculated, as indicated in the notes on "Heat Run," from the equivalent resistance of the transformers obtained at the beginning and the end of the test.

The equivalent resistance of the transformer (for the meaning of this term see the notes on Core and Copper Losses of a Transformer), can be obtained from the readings of W_2 and A_2. $\frac{W_2}{2}$ is the copper loss of one transformer. This is equal to I_2^2R' where R' is the equivalent resistance of the transformer referred to the secondary side and I_2 is the secondary current given by the ammeter A_2.

Due to the fact that the wattmeter will be reading on a poor part of its scale on account of low power-factor, it is more accurate to calculate the rise of temperature from the resistances of the transformer obtained by the drop of potential method, immediately before and after the test.

Since it is possible to obtain the rise in temperature from the wattmeter reading, a curve of rise of temperature with time may be plotted provided readings of W_2 and I_2 are taken at regularly timed intervals during the test.

In the time allowed for the laboratory exercise there probably will not be more than time to get the transformers connected and operating under full-load conditions. Readings should be taken, however, for the calculation of efficiency. Readings for temperature rise may be omitted.

Efficiency.—The full-load efficiency of the transformers under test will be given by the rated output divided by their rated output plus their full-load copper and core losses.

$$\text{Efficiency} = \frac{\text{Rated Output}}{\text{Rated Output} + \text{core loss} + \text{full-load copper loss}}$$

$$= \frac{\text{Rated Output}}{\text{Rated Output} + \frac{W_1}{2} + \frac{W_2}{2}}$$

where W_2 and W_1 represent the readings of the two wattmeters when the transformers are under full-load conditions.

Since the core loss is practically constant and the copper loss varies inversely as the square of the current, the efficiency at any load may be easily found.

For example:—The efficiency at half load will be

$$\frac{\text{Output for 1-2 load}}{\text{Output for 1-2 load} + \frac{W_1}{2} + \left(\frac{1}{2}\right)^2\left(\frac{W_2}{2}\right)}$$

at one-quarter load:

$$\frac{\text{Output for 1-4 load}}{\text{Output for 1-4 load} + \frac{W_1}{2} + \left(\frac{1}{4}\right)^2\left(\frac{W_2}{2}\right)}$$

Results Required:—Plot of efficiency and output from no-load to full-load, the efficencies should be calculated for one-eighth, one-quarter, one-half. one-third and full-load. Rise in temperature provided the time permits of a run of at least one-half hour.*

*In an actual test the rise in temperature should be measured by thermometer as well as by resistance. If a heat run alone is to be made, the only instruments required will be the two ammeters and voltmeter V_1. If extension coils are used with either wattmeter, do not forget to multiply its readings by the proper factor.

XXVIII

THREE-PHASE TRANSFORMER CONNECTIONS.

This experiment is to illustrate the different voltages obtained by the use of three similar transformers in connection with a three-phase system.

Three similar 1.5 kw., 60 cycle, 2:1(230^v:115^v) transformers will be employed in connection with the 230-volt three-phase laboratory circuit.

The experiment will consist in connecting the transformers in the different possible ways and measuring the voltages.

The different transformer connections are given below together with a diagramatic representation of the connections. The voltages are also indicated. In every case 230 volts will be applied to the primary side of the transformer system.

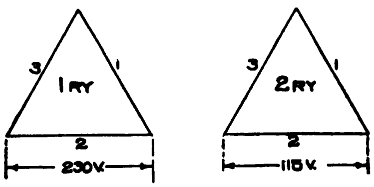


Fig. 80

a. Primaries in △.

Secondaries in △.

b. Primaries in Δ.
Secondaries in Y.

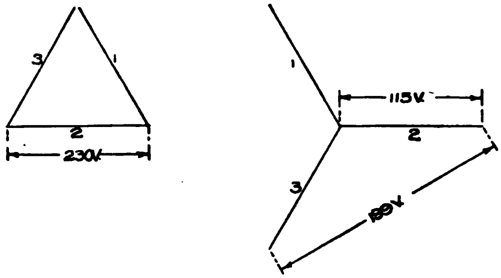


Fig. 81

c. Primaries in Y.
Secondaries in Y.

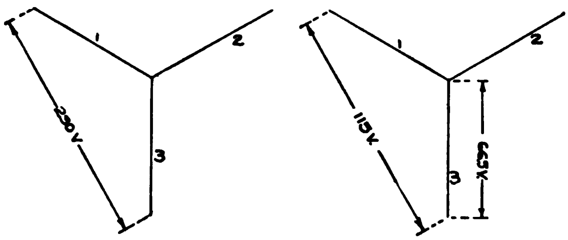


Fig. 82

Note:—The 66.5 volts between the lines and neutral on the secondary side cannot be used unless a neutral is also used on the primary side or the transformers have a common iron core.

d. Primaries in Y.
Secondaries in Δ.

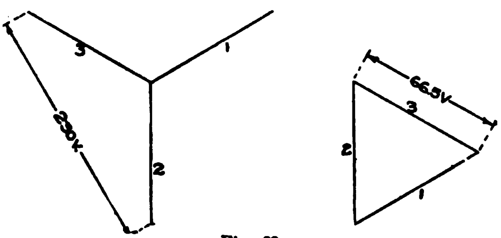


Fig. 83

Unless the three transformers have a common iron core, this method of connection cannot be used without a prohibitive unbalancing of voltage, unless a neutral is connected on the primary side.

e. This is the so-called V connection and is the same as *a*, with one transformer removed.

Procedure:— First connect each transformer with its primaries in series and its secondaries in parallel. The simplest method of

Note:—When transformers are connected as shown in *a*, the burning out of one of the three transformers will not interrupt the service. The remaining two will supply the three phases at a diminished output.

doing this is as follows. Take each transformer separately. Connect the two coils which are to be used as primaries together as shown in Fig. 84, and apply voltage to one of them. This voltage should not be much in excess of that for which the coil is designed. The separate coils of the transformers used in this experiment are for 115 volts each, and the voltage between the line and neutral of the 230 volt, three-phase system may be applied to them.

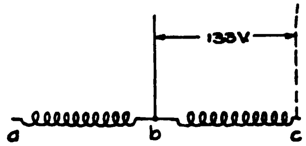


Fig. 84

If the coils are properly connected to put them in series, a voltmeter placed across a and c, Fig. 84, will indicate twice the voltage applied to the single coil bc. If the voltmeter reads zero reverse the coil ab. If it is desired to put the coils ab and bc in parallel, they should be connected so that the voltage between a and c is zero. The points a and c may then be connected together, putting the coils in parallel.

Having connected the primaries in series, connect them to the 230-volt mains, and connect the two secondaries together and measure the voltage between the two free terminals. If this voltage is zero the free ends may be connected together and the coils will be in parallel. If the voltage between the free ends is double that between the terminals of a single secondary coil the secondaries will be in series. In this case, the free ends *must not be connected.*

a. Primaries in $\triangle$.
Secondaries in $\triangle$.

Connect the primaries in $\triangle$ and to the mains, then connect one end of each of two of the secondaries together. The voltage between the free ends will be either 115 or $115\sqrt{3}=199$. If it is the latter, reverse the connections of one of the secondaries. Now connect the end of the remaining secondary to one of the free ends of the other two. The voltage across the gap will now be zero. The gap may now be closed, putting the secondaries in $\triangle$.

Measure the secondary and primary voltages, then apply a load to each of the phases separately, then load all three phases at once to see if the system works properly.

Open the main switch and remove one transformer. This will leave the remaining two connected in *V*. Measure the ratio of voltages and try loads on the three phases as before.

b. Primaries in $\triangle$.
Secondaries in *Y*.

NOTE.—To avoid short-circuiting, open the main switch when making changes in the connections.

Connect the primaries again in Δ, then connect one end of two of the secondaries together. For Y-connection, the voltage between the free ends of the two secondaries should be $115\sqrt{3}=199$. If it is not 199, reverse the connections of one of the secondaries. Now connect one end of the secondary of the third to the common connection between the other two. If the voltage between the free end of this last secondary and the free ends of the other two is not 199, reverse the connections of the last secondary. The secondaries will now be connected in Y.

Measure the ratio of voltages, then try applying both balanced and unbalanced lamp loads to the three phases. Try the load in Δ, and also in Y, with the neutral brought out from the point of common connection of the secondaries.

c. Primaries in Y.
Secondaries in Y.

Connect the primaries in Y, then connect the point of common connection of the primaries through a switch, which may be opened independently of the main switch, to the neutral wire of the laboratory system. Connect the secondaries in Y, following the directions given under (*b*). Measure the ratio of voltages, both Δ and Y, then try loading the system first in Δ then in Y with neutral. With a balanced Y-load try the effect of opening the switch in the primary neutral. Try same with an unbalanced load.

d. Primaries in Y.
Secondaries in Δ.

Disconnect the secondaries, then connect them, following the directions under (*a*).

With the neutral switch on the primary side closed, measure the ratio of primary and secondary voltages. Try loading the system with both balanced and unbalanced loads. Note the effect on the system when loaded with an unbalanced load, of opening the neutral switch on the primary side. This will complete the test.

The report should contain a brief statement of the results of the experiment.

XXIX

SYNCHRONOUS MOTOR

A direct-current motor can never run with an armature voltage which is greater than, or even as great as the voltage impressed on its terminals. A synchronous motor, on the other hand, may be operated even though its armature voltage is considerably greater than the voltage at its terminals. The possibility of running under this condition, or over-excited as it called, is due to the phase displacement of the current with respect to the electromotive force.

A synchronous motor must run, up to its limit of output, in synchronism with the generator. Its speed therefore is fixed by the speed of the generator and will be equal to the frequency of the circuit from which the motor is run multiplied by sixty and divided by the number of pairs of poles on the motor.

The power factor of a synchronous motor operating at a fixed terminal voltage is determined by its excitation. The excitation which makes its power factor unity, is called the normal excitation. If a synchronous motor is over-excited, it will take a leading current from the line and will act like a capacity or condenser load. If this motor is under-excited it will take a lagging current from the line and will be equivalent to an inductive load.

Synchronous motors which are used for power purposes are generally slightly over-excited at no load as this increases their stability under load. Under this condition the power factor will rise to unity as the motor is loaded, reach unity and then fall again.

The load at which the power factor becomes unity will depend upon the impressed voltage, the frequency and the motor field current. The field current for unit power factor at any load may be found by varying the field current until the armature current is a minimum.

Curves showing the variation of amature current with field current for different constant outputs are called, from the shape, the *V*-curves. These curves may be plotted with line currents if more desirable. A *V*-curve of a synchronous motor is shown in Fig. 85.

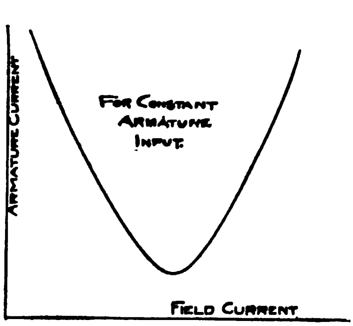


Fig. 85

The lowest point of this curve gives the field current for unity power factor for the load for which the *V*-curve is drawn. Field currents less than this will cause the motor to take a lagging current from the line while greater field currents will cause the motor to

take a leading current. The possibilty of making a synchronous motor take either a lagging or leading current renders a motor of this type particularly valuable in connection with power transmission.

Synchronous motors may be used over-excited to balance an inductive load on the line and produce unit power factor. They may also be used over-excited at the end of a transmission line to regulate the voltage. Synchronous motors cannot, however, be used for this latter purpose unless there is reactance in the line between the motor and the generator. With line reactance it is perfectly possible by over-exciting the motor to have the potential at the motor end of the line greater than at the generator end. The possibility of producing a rise in voltage by a leading current is shown by Fig. 86.

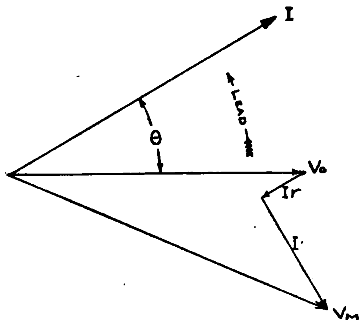


Fig. 86

V_g represents the voltage at the generator end of the line. I is the line current leading the generator voltage by an angle θ. The voltage of the motor end will be the generator voltage minus, vectorially, the resistance and reactance drops in the line.

Ir represents the resistance drop subtracted from V_g; Ix represents the reactive drop of the line subtracted. V_m is then the voltage at the motor which, as will be noticed, is greater than the generator voltage V_g. The amount by which this is greater will be dependent upon the values of r and x, i.e., the resistance and reactance respectively of the line, the angle of lead, θ, and the line current.

A synchronous motor, as such, is not self-starting. Some kind of a starting device must always be used for single-phase motors. These latter are seldom used, but when they are, they are generally started by bringing them up to speed with their direct-current fields on, by a separate motor then, adjusting their voltage, phasing or synchronizing them, and throwing them on the line as if they were generators. After a motor of this type has been connected to the line the auxiliary starting motor may be shut down.

Polyphase motors may be started without load as induction motors. If a polyphase synchronous motor be connected to the mains with its direct-current field open, it will start and come up to speed as an induction motor due to the eddy currents and hysteresis losses produced in the pole faces of field magnets, by the revolving magnetic field in the stator. If, when the motor is up to speed, its direct-current field be gradually thrown in, the motor will come

into step and run as a synchronous motor. Synchronous motors which are provided with a suitable amortisseur winding may be brought up to speed under load.

If a motor of any size is thrown directly on the line, as indicated above, a very heavy lagging current will flow which will seriously disturb the voltage of the mains. To avoid this, polyphase synchronous motors, except in the smaller sizes, are started with reduced voltage from a compensator. The potential induced in the direct-current field at starting may be very great. Hence to avoid danger of puncturing the field, the field circuit should be broken in a number of different places in order that the potential induced in any one section shall not be great enough to cause damage. The necessity for sectionalizing the field may be avoided by insulating the field coils for high voltage.

The experiment on the synchronous motor will be divided into two parts. The first part will be to determine the ordinary motor curves, while the second part will show the rise of voltage produced by an over-excited synchronous motor on a line containing reactance.

PART I.

A small three phase synchronous motor will be used. A compensator will be provided for starting it.

Procedure:—Connect the motor according to Fig. 87, using the two wattmeter method for measuring power. Fig. 87 shows a △ connected motor. A Y connected motor could be used equally well.

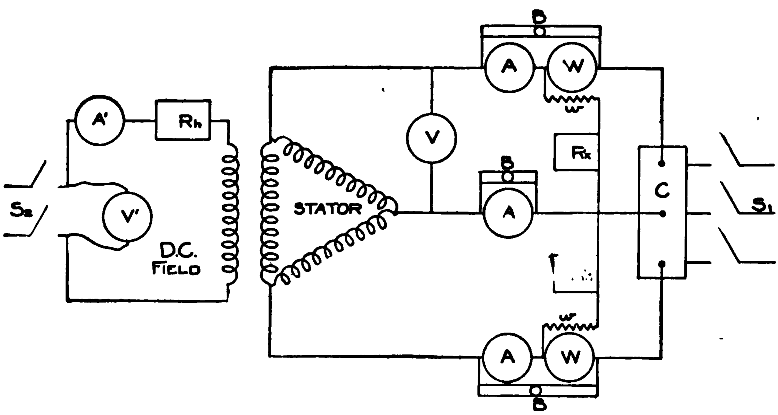


Fig. 87

C is a compensator for furnishing the reduced voltage required for starting the motor. The circles marked A are the ammeters, while the circles marked W are the current coils of the wattmeters. The zigzag lines marked w represent the potential coils of the wattmeters and the squares marked R_x are the extension boxes for the wattmeters. These boxes may or may not be required. Since the load will be balanced, one voltmeter V, will be sufficient. A

direct current voltmeter, V' and a direct current ammeter A' will be required for the motor field.

When the connections have been properly made, short circuit the wattmeters and ammeters, loosen the brake, and close S_1 connecting the stator of the motor to the mains and bring the motor up to speed by means of the compensator.*

When the motor is up to speed, which ought not to take over a few seconds, close S_2 and apply full voltage to the stator of the motor. Then adjust the current in its field to make the line current a minimum.

Load the motor until it takes three-fourths its rated current, then slowly change the motor field current until the line current is a minimum. Record this value of the field current. This is the field excitation for the load test. The power-factor of the system will now be unity, and consequently the two wattmeters should read alike.

Throw the load off of the motor and read all the instruments including the spring balance. Also record the frequency of the circuit. The speed of the motor in revolutions per minute may be found by dividing the frequency of the circuit multiplied by sixty by the number of pairs of poles on the motor.

Increase the load on the motor to about one and one-fourth times its rated load in about eight steps recording the readings of all the instruments at each step. The field excitation must be kept constant during the entire run. If there is any means of controlling it, the frequency of the circuit from which the motor is operated should also be kept constant. If the motor should reach its maximum load during the test and break down, i.e., fall out of synchronism, immediately open the main switch.

This will complete the work for Part I.

From the data obtained, calculate and plot the following curves: power-factor and output, efficiency and output, and torque and output. Plot the outputs as abscissae. Indicate on the plot the average speed found during the test.

PART II.

Four curves are required in this part of the test on the synchronous motor, namely: a no-load V-curve and three curves showing the relation between the rise of voltage at the motor for the three following conditions, (*a*) with neither resistance nor reactance in series with the motor, (*b*) with resistance in series with the motor and (*c*) with reactance in series with the motor.

*Before closing the Switch S_1 ask what special precantions it is necessary to take when starting a sychronous motor.

All four curves should be on the same sheet and should be similar to those shown in Fig. 88.

The curves shown in the order in which they are numbered are, respectively, the *V*-curve, the curve showing the voltage rise due to reactance, the curve showing the voltage rise with neither reactance nor resistance in circuit, and the curve showing the rise with resistance.

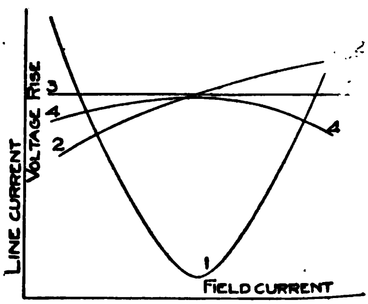


Fig. 88

It is important to notice that no rise in voltage can be obtained unless there is reactance in series with the motor. It should also be noticed that little change in voltage can be produced with the reactance in circuit unless the motor is over or under excited.

The same motor as was used in Part I will be used in Part II. In addition, a three-phase or three single-phase reactances and three similar resistances will be required. These will be placed in series with the motor and must, therefore, be capable of carrying the line current without dangerous heating.

Procedure:— Connect the motor according to Figure 89. The circles marked *R* represent either the reactances or resistances according to which are being used. Except for the addition of the reactances or resistances and the omission of the wattmeters and the addition of a second voltmeter, the connections are the same as those used for Part I.

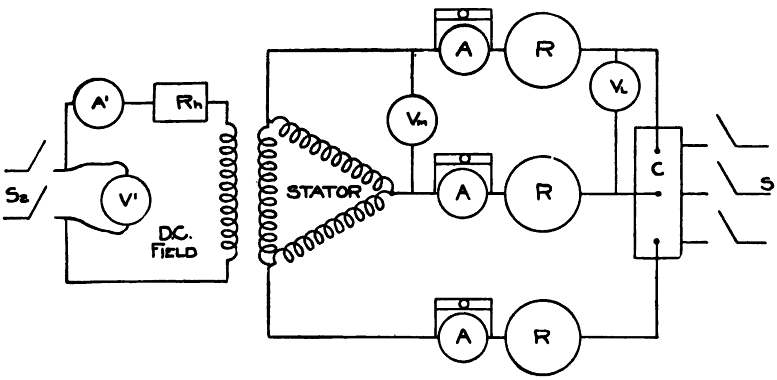


Fig. 89

V-**curve:**—This should be taken with neither resistance nor reactance in series with the motor. Bring the motor up to speed, according to the directions already given, and adjust its field excitation for minimum armature current. Record the readings of

all instruments. Now increase the excitation until the motor takes about one and one-quarter full-load current from the mains and again record the indications of all instruments. Decrease the field in about ten steps until the current taken by the motor has passed through a minimum and has again risen to about one and one-quarter full-load current. Take readings at each step. From the readings obtained in this way plot a *V*-curve using line currents as ordinates and field currents as abscissae.

Curves of Voltage Rise, *a.* **With neither resistance nor reactance:**—Data for this can be obtained while making the test for the *V*-curve by recording the readings of the two voltmeters, one on the mains and one at the motor terminals. Since there is neither resistance nor reactance in the line between these two instruments they should both read alike.

b. **Curve with resistance:**—Insert the three non-inductive resistances, one in each line between the mains and the motor and take readings of all instruments as the line current is varied from one and one-quarter full-load current leading (corresponding to over excitation) to one and one-quarter full-load current lagging (corresponding to under excitation). This change in line current is obtained by varying the field excitation over the same range as was used for the *V*-curve. Plot the difference between the readings of the voltmeter at the motor and at the mains as ordinates with field currents as abscissae. Call an increase in voltage positive.

c. **Curve with reactance:**—Replace the resistances by the reactance and then proceed as under *b.*

XXX

PARALLEL RUNNING OF ALTERNATORS

The conditions for successful parallel operation of alternators are:—

a. That the generators shall have the same frequency.

b. That the generators shall be in conjunction with respect to the external circuit.

c. That the generators shall have the same armature potential.

d. That the wave forms of the alternators shall be the same.

e. That the characteristics of the alternators and their prime-movers shall be the same.

Condition a. Needs no explanation.

Condition b. The condition of opposition requires that the polarity of any two generators, when considered with respect to their series circuit, shall be opposite at every instant.

In Fig. 90 the signs indicate the polarity at some particular instant of two alternators which are in parallel. It will be noticed that the two generators are acting together, i.e., in conjunction, with respect to the external circuit, but they are in opposition when considered in respect to their own or the series circuit.

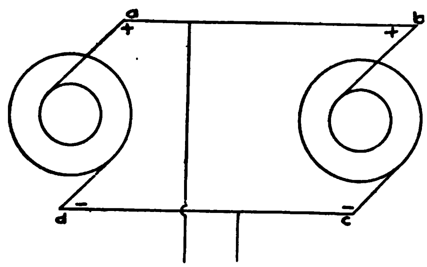


Fig. 90

Opposition on their own circuit is the natural condition of two alternators which are connected in parallel. If they tend to depart from this condition a resultant electromotive force will be produced which will cause a current to flow in the series circuit consisting of the two armatures which will make the generator, which is behind its proper phase position, drop a part of its load, and the generator which is ahead take more load. The effect will be to speed up the first and slow down the second and bring the two back into the proper phase relation.

This action is readily shown by a vector diagram. Let E_1 and E_2, Fig. 91, be the armature potentials of two equal generators which are in exact opposition on their own circuit. Suppose that in some way E_2 gets slightly ahead of its proper position. Let this position be represented by E'_2 in Fig. 91. A resultant electromotive force E_0 will be produced, acting in the circuit *a b c d* in Fig. 90. This electromotive force will cause a current $I_0 = \frac{E_0}{z_0}$ in the circuit *a b c d*, which will lag behind E_0. z_0 is the resultant impedance of the two generators in series.

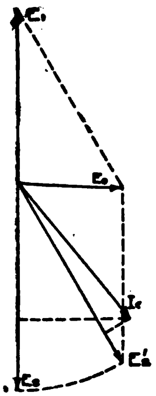


Fig. 91

The power developed by an alternating current is $IE \cos \theta$ where θ is the angle of lag of the current behind the voltage.

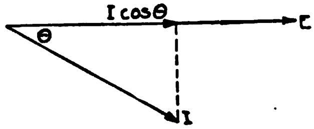


Fig. 92

$I \cos \theta$ is the energy component of the current with respect to the electromotive force and is the projection of the current on the electromotive force vector. If this projection is in phase with the electromotive force, generator action will be developed. If it is opposite in phase to the electromotive force, motor action will be developed.

It will be noticed that the projection of I_0 on E'_2 is in phase with E'_2, while the projection on E_1 is in opposite phase to E_1. The current I_0 with respect to generator *No. 2* represents generator action, while with respect to generator *No. 1* it represents motor action. The result is a slowing down of generator *No. 2* and a speeding up of generator *No. 1*. This action will continue until the generators are brought back into opposition. This interchange of current I_0 is sometimes, though improperly, called the synchronizing current. The true synchronizing current is the component of I_0 which is effective in bringing the generators into step. Since the natural tendency of two generators working on the same circuit is to come into opposition, it is impossible except in one case, which is of no practical importance, to operate alternators in series.

Condition c. If one generator has a greater armature potential than the other, there will be a resultant potential acting in the series circuit consisting of two generators. This will cause a current which will lag with respect to the generator of greater e.m.f. and will lead with respect to the other. Since a lagging current in a generator will cause, by its armature reaction, a decrease in the terminal voltage of the generator, and a leading current will cause an increase in this voltage, the effect of the interchange of current will be to offset any attempt to increase the voltage of one generator over that of the other. The interchange of current between the generators in the above case will be just sufficient to make their terminal voltages equal. Although the generators will continue to operate with interchange of current, they will operate at a decreased efficiency due to the increase in the copper loss caused by the current interchange.

Condition d. If this condition is not fulfilled there will be an interchange of current between the machines even though the other conditions are fulfilled.

Condition e. If the characteristics of the prime movers, i.e., their change in speed with change in load are the same, the alter-

nators will divide the load automatically in proportion to their capacities. If, on the other hand, the characteristics of the prime movers are not the same, the alternators will not divide the load properly.

Prime-movers for alternators must always have drooping characteristics, consequently any increase in load will be accompanied by a drop in speed.

The distribution of load between two or more direct-current generators in parallel can be varied by the field excitation. Any attempt to make an alternator, which is operating in parallel with others, deliver more power by merely increasing its field current, will result in failure, since an alternator in parallel with others cannot slow down as a direct-current generator can, and thereby receive more power from its prime-mover. The improper excitation of alternators which are connected in parallel will cause a large interchange of current between them.

The distribution of load between alternators in parallel can only be told by the readings of the wattmeters in each machine circuit. If the load on an alternator is to be increased, it must be done by increasing the driving torque of its prime-mover. If the prime-mover should be an engine, it must be given more steam. It will be necessary to increase the field of the alternator at the same time, but this is merely to make up for the increased armature-impedance drop and has nothing whatever to do with making the machine take load. The load is controlled entirely by the driving torque of the prime-mover.

In order to throw an alternator in parallel with others which are already working, it must first be brought up to speed and its voltage made equal to that of the other generators. The speed of its engine or prime-mover is then varied until the alternator is running in synchronism, i.e., with the same periodicity, and in opposition to the other generators. The switch connecting the alternator to the bus-bars may then be closed.

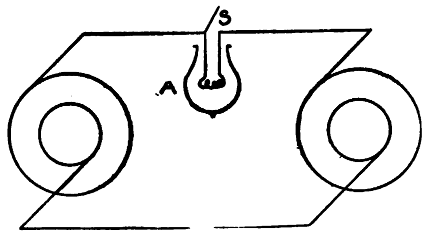


Fig. 93.

To make the alternator take load, the driving torque of its prime-mover is increased, and, to make up for the increase in the armature-impedance drop, the field excitation of the generator is also increased.

Some form of synchronizing device must be used for telling when the incoming alternator is in opposition to the others. The simplest form of synchronizer, and one which is perfectly satisfactory for small alternators, is an incandescent lamp connected in series with the alternator and bus-bars, before the main switch is closed, If high-voltage alternators are to be synchronized, transformers will be required in connection with the lamp.

If a lamp be placed at A, Fig. 93, it will be bright when the generators are in conjunction on their series circuit. In this case it will receive twice the voltage of either generator. It will be dark when the generators are in opposition. If one generator is running slightly faster than the other, the lamp will flicker. The generator which is being synchronized should be connected to the bus-bars when the lamp is dark. The speed should first, however, be adjusted so that the lamp requires several seconds in going from bright to dark.*

When large generators are to be synchronized, some form of synchronizer more accurate than a lamp should be used.

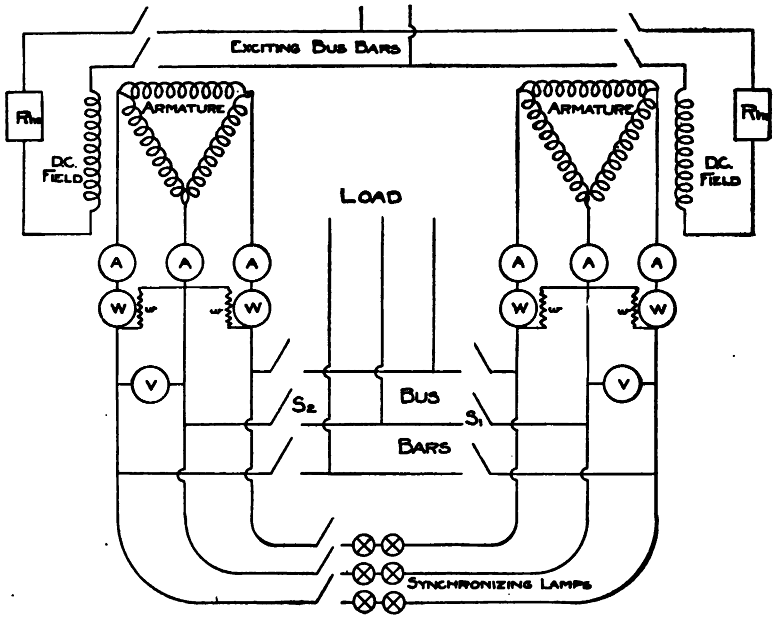


Fig. 94

It is well to throw the incoming generator in parallel when it is running fast rather than slow.

If three-phase generators are to be synchronized, lamps will be required for each phase. These should all be dark at the same time. If they are not, it shows that like-phases are not connected together.

Two three-phase, similar alternators, driven by similar direct-current shunt motors will be used in this experiment.

The proper connections for the alternators are shown in Fig. 94.

*If transformers are used in connection with the synchronizing lamp, it is possible, by reversing the connections of the secondaries of one of the transformers, to have the lamp show bright when the generator should be thrown in.

The circles marked *W*, represent the current coils of the wattmeters. The ammeters are marked *A*, the voltmeters, *V*. The The potential coils of the wattmeters are marked *w*.

Lamps of the proper voltage will be used in each phase for synchronizing lamps. The maximum voltage on these lamps will be the line voltage multiplied by $\frac{2}{\sqrt{3}}$.

Procedure:—Connect the alternators as shown in Fig. 94, using two polyphase wattmeters in place of the four wattmeters shown. One voltmeter for each generator will be sufficient.

With all switches used in connection with the alternators open, start the shunt motors and bring the alternators up to speed. Adjust the speed of the alternators by means of the rheostats in the fields of the motors until the alternators run at rated frequency.

Close the alternator fields and adjust their terminal voltage to the rated value. Now close the small switch on the synchronizing lamps, and slowly vary the speed of one of the alternators by moving the rheostat in the field of the shunt motor which drives it one notch at a time, until four or five seconds are required for the synchronizing lamps to go from bright to dark. Close S_1 and see that the voltage of each alternator is the same, then when the lamps are dark close S_2.

The alternators will now be working in parallel but should be delivering no load. If the voltage and speed have been properly adjusted, there should be no interchange of current between the generators and the ammeters should read zero.

Now load the alternators to what corresponds to about the full load of one. The load should be kept balanced by keeping the currents in the three phases, as indicated by the ammeters, equal.

Take the readings of the wattmeters and the ammeters after each change in load.

If the power output of one generator increases faster than in the other, it shows that the speed characteristics of the driving motors are not exactly the same, or it may possibly show belt slip. If, on the other hand, the power outputs increase together but the current in one generator increases faster than in the other, it shows that the characteristics of the alternators are not the same. The two motors and the two alternators are the same, their characteristics should be nearly identical and the watts and amperes in each machine circuit ought to increase at nearly the same rate. The speed characteristics of the motors may, however, be changed considerably by a slight movement of their brushes.

If, when the total load on the system has been adjusted to what corresponds to about the full load for one alternator, the loads on the two generators as indicated by the wattmeters, are

not the same, make them so by slowly increasing the driving torque of the motor connected to the alternator delivering the least power. A decrease in the motor field will increase its torque.

Now adjust the voltage of the system to its rated value by slowly increasing the field of both generators in such a way as to keep the ammeter readings in each machine circuit the same.

When this has been done try the effect of an attempt to shift the load from one generator to the other by increasing the field current of one generator. Note the readings of the wattmeters, ammeters and voltmeters.

Adjust the field of the generator until the ammeters in the two machine circuits again read alike and the voltage of the system is approximately normal, then take one generator out of service by slowly decreasing the driving torque of its motor at the same time weakening the field of the generator which is being taken out and increasing the field of the other in such a way as to keep the potential of the system constant and the currents in each generator approximately a minimum for the power it is delivering. When the wattmeters and ammeters of the generator which is being taken out read zero, open the switch connected to the bus-bars.

Try synchronizing the generator and again putting it back into service and making it take all the load.

If, when an alternator is being taken out of service, the driving torque of its prime-mover is reduced below that value which makes the readings of the wattmeters in its circuit zero, the alternator will act as a synchronous motor and will deliver power to its prime-mover.

XXXI

ROTARY CONVERTER

It is frequently necessary to transform alternating current to direct current and vice versa. Such a transformation may be accomplished by a motor-generator set, consisting of a direct-current generator coupled mechanically to either a synchronous motor or an induction motor, or by a rotary converter. The motor generator and rotary converter each possess certain inherent advantages and disadvantages.

A rotary converter is essentially a direct current shunt or compound generator with taps brought out from the armature to slip rings, the number of these taps depending upon the number of phases. Copper damping bridges are attached to the poles to prevent hunting.

Since there is but a single winding on the armature of a rotary, any conductor in this winding must carry at each instant the resultant of the motor and generator currents. Although the heating in all parts of the armature due to this resultant current will not be the same, the total heating due to the resultant of the motor and generator currents will be less, except in the case of the single-phase machine than that which would be caused by either the direct or the alternating current alone. Consequently, the output of any but a single-phase rotary converter, will be considerably greater than the output of the same converter, used as a simple motor or generator.

The theoretical rating at unit power-factor of a rotary as compared with its rating as a direct-current generator, is:—Single phase, 0.85; three-phase, 1.32; four-phase, 1.62; six-phase, 1.92. These values are based on an assumed efficiency of 100 per cent and a sine wave of current. The total losses in a rotary converter will be somewhat less than half of the total losses in the two machines required for a motor-generator set of equal output.

Since the armature of a converter carries the difference between the alternating and the direct currents, the armature reaction of a converter will be small, and for this reason, no change in brush position will be required with change of load.

The ratio of transformation of a rotary converter with a fixed brush position is fixed, except in so far as it is influenced by wave form. It depends merely upon the number of slip rings or phases. The ratio of terminal voltages will, of course, differ slightly from the true ratio of transformation on account of the resistance and reactance drops in the armature winding. Changing the field excitation will not affect the ratio of transformation.

The ratios of transformation of converters with different numbers of phases are:—

Single-phase	0.707
Three-phase	0.612
Four-phase	0.500
Six-pase	0.354

These ratios are the ratios of the alternating to the direct voltage.

If a rotary converter is running from the alternating-current side, an increase in the execitation will not affect the speed, but will cause the rotary to take leading current from the line. If the line contains reactance, an increase in the voltage impressed on the rotary will be produced and, as the result of this, the direct-current voltage will rise. (See page 108, under Synchronous Motor). Reactance is often artificially placed in a line, in order to obtain control of the voltage on the direct-current side of a converter. If more than a moderate variation in voltage is required, i.e., over about 10 per cent, some form of potential regulator must be used between the rotary and its transformers.

Rotary converters are seldom operated from the direct-current side, or inverted, as it is called. When so operated, some device for limiting the speed must be used, since an inductive load will produce a demagnetizing effect on the field, and cause the rotary to speed up. A large lagging current or a short-circuit will cause a converter to race, and, if its speed is not limited automatically, it may speed up to the bursting point.

Alternating current is, as a rule, transmitted at high voltage. Direct-current voltages, on the other hand, seldom exceed 700. This usually necessitates the use of transformers between the line and a rotary converter in order to obtain the proper direct-current voltage. These transformers somewhat increase the cost of the rotary-converter set, and they slightly lower its efficiency.

Starting Rotary Converters:—A rotary converter may be started in three different ways. 1st, as a direct-current motor from the direct-current side. In this case it has to be synchronized. 2nd, by an auxiliary motor on the shaft. An induction motor is generally used for this purpose. In this case the machine must also be synchronized. 3rd, as an induction-motor with its direct-current field left open until the converter is up to speed. In this last case no synchronizing is necessary but unless the field is separately excited there is no way of predetermining the polarity of the converter before the field is closed. The polarity of a self-excited rotary depends upon the position of the armature with respect to the poles at the instant the field circuit is closed. When a converter is started as an induction motor there will be a high voltage induced in its field winding by the transformer action which exists between it and the armature. This transformer action will cease as soon as synchron-

ous speed has been reached. Danger to the field winding is avoided by opening it in several places so as to diminish the total voltage acting on the insulation of any one section.

Test:—This test will be performed on a small three-phase rotary converter. The rating of the converter assigned should be obtained from its name plate. In order to get the correct voltage for the alternating-current side of the converter transformers will be required. Either three single-phase transformers connected for three phase, two *T*-connected transformers, or one three-phase transformer may be used. The method of connecting the transformers will be indicated in the assignment. The converter will be started by means of a compensator placed between the transformers and the converter. Data should be obtained for the following curves loading the converter on its direct current side.

Efficiency and *K. W.* output.
Power-factor and *K. W.* output.
Direct-current voltage and *K. W.* output.
Alternating-current and *K. W.* output.

In obtaining the above curves, consider the transformers and rotary as a unit, putting the alternating-current instruments outside of the transformers in order to measure the total input to the system.

The diagram of connections is shown in Figure 95.

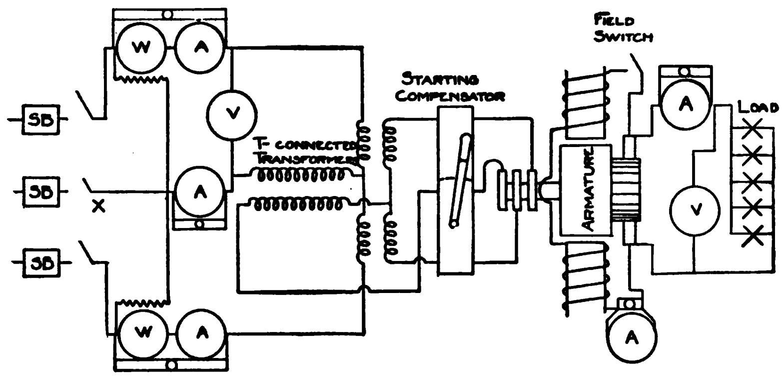


Fig. 95

The transformers shown in Figure 95 are *T*-connected. This does not, however, mean that *T*-connected transformers will necessarily be used.

Make the connections according to Figure 95. See that the compensator handle is in the position marked "off", then open the sectionalized field switch (not shown in diagram). Now close the main line switch *A* and swing the handle of the compensator into the first marked position. If the rotary starts in the wrong

direction, i.e., against the alternating current brushes, open the switch X and interchange any two of the three alternating current leads at the rotary. If the rotary starts in the proper direction, put the handle of the compensator in successive positions as the machine speeds up. When the next to the last position is reached wait until the rotary is running at or near synchronous speed, then close the field switch and swing the handle of the compensator quickly into the running position. In this position the compensator is entirely cut out. If the rotary slows down as soon as the field is closed, the main switch should be opened immediately. If the rotary fails to start when the compensator is put in the second position, open the main switch, A, and look over the connections. Probably there is an open circuit in one phase. If the rotary fails to build up when the field is closed and sparks badly at the commutator, the field connections are probably reversed or the direct current brushes are not in their correct position.

As soon as the field circuit has been closed, and the compensator has been put in the running position, cautiously remove the short-circuit from one of the alternating current ammeters and adjust the field current of the rotary, so as to make the alternating current ammeters read approximately a minimum. Now apply about three-quarters load. Readjust the field to produce a minimum line current for this load, then read the field current. This is the field-current which will give unit power-factor at three-quarters load, and is the field current which should be used throughout the load test. It should be kept constant by adjusting the field rheostat.

Throw off the load and record the readings of all instruments. Add about one-eighth load and again read the instruments. The frequency should also be recorded. Proceed in this way until about one and one-fourth full load has been reached. Now reduce the load to about three-quarters and note the rise in the direct-current voltage, produced by an increase in the field-excitation, also note the effect of this on the power-factor. The change in the voltage, which is produced by altering the field-excitation, is not due to a change in the ratio of transformation of the rotary, but is caused principally by the rise in voltage through the transformers. The rise in voltage through the transformers is due to the leading current produced by the over excitation of the rotary. If the transformers and rotary were without reactance, no change of voltage could be produced by field excitation. Under excitation will cause a lagging current and a fall of voltage.

XXXII

ALTERNATING-CURRENT SERIES MOTOR

The armature and field of a series motor are connected in series. Consequently, if an alternating current be sent through such a motor, the current in the armature and field will be in phase at every instant. A series motor will, therefore, develop a torque, which, though intermittent, will always act in the same direction. The direction in which this torque acts, depends upon the relative directions of the current in the armature and field, and it may be reversed by merely reversing the connections of either the armature or the field. Due, however, to the large core losses and high reactance of a direct-current series motor, a motor of this type will develop very little torque or power when used on alternating-current circuit.

A series motor intended for use on alternating current-circuit must necessarily have both its field and armature cores laminated and, moreover, in order to develop satisfactory torque and power-factor characteristics, it must have the ratio of armature to field turns relatively large. This reduces the field reactance and correspondingly increases the armature reactance but this latter can be nearly neutralized by the use of a compensating winding placed on the stationary part of a motor, in such a position as to oppose and neutralize the magnetic field, produced by the armature current.

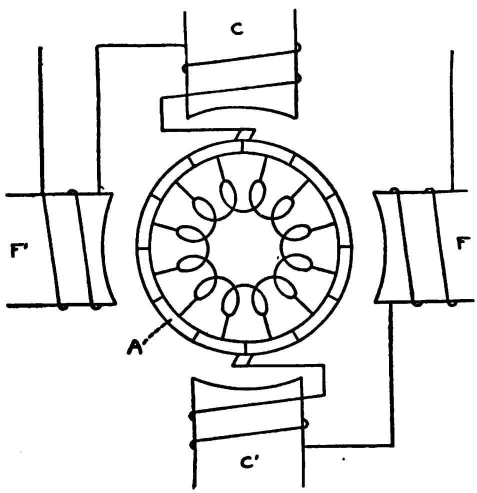


Fig. 96

The compensating winding may be either short-circuited on itself and receive its current by the transformer action between it and the armature, in which case the coil and the armature act inductively like a short-circuit transformer, or it may be connected in series with the armature, as it must be, when the motor is used on both alternating and direct-current circuits.

When the compensating winding is short-circuited, the motor is said to be inductively compensated; when it is in series with the armature and the field; the motor is said to be conductively compensated.

A two-pole motor with a series-connected compensating field is shown in Fig. 96.

F and *F'* are the main fields.
C and *C'* are the compensating fields.
A is the commutator.
The curved lines inside of *A* represent the armature winding.

The straight lines joining the armature windings to the commutator are resistances. These will be mentioned later.

The sparking which tends to occur in a series alternating-current motor is one of the inherent difficulting in the design of a motor of this type. During commutation, the brushes on any commutator motor short-circuit the armature coils under them. These short-circuited coils are in the most favorable position to have a current induced in them by the alternating-field flux, and unless this induced current is diminished in some way, destructive sparking and heating of the short-circuited coils and commutator will result.

The usual way to diminish this short-circuit-current is by the the use of small resistances inserted between the armature coils and commutator bars. These resistances naturally increase the resistance of the armature between the brushes and, consequently, increase the copper loss in the main armature circuit, but if the resistances are properly adjusted, the increase in the armature copper loss is more than balanced by the decrease in the heating in the coils short-circuited during commutation, and, moreover, commutation is rendered possible. A little thought will show that two resistances are in parallel with respect to the external circuit, and two in series with respect to the short-circuited armature coils.

Series motors for alternating current operation are inherently low frequency machines. The use of high frequency would cause prohibitive reactance. Small alternating-current series motors are generally controlled and have their speed varied by series resistance, large motors, however, are controlled by varying the impressed voltage by means of a compensator.

Test:—The rating of the motor assigned for this test will be found on its name plate. A friction brake will be used for loading the motor.

Any series motor will increase its speed rapidly as the load on it is decreased. For this, reason care must be taken in handling the brake. The motor should be started under load, and the load must not be reduced so far as to make the speed dangerous. Ask what the safe limit of speed is for the particular motor assigned.

This test will be similar to the one on the direct-current series motor described on page 22. A wattmeter, of course, must be

used for measuring the input to the alternating current series motor. The proper connections for the test are shown in Figure 97.

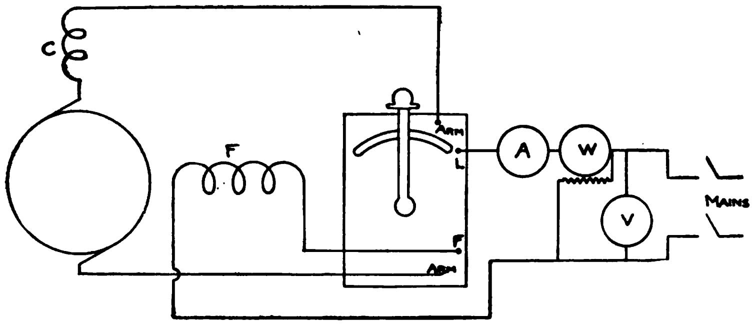


Fig. 97

C is the compensating field.

F is the main series field.

S is the starting device or speed controller. This may be either a compensating or a variable resistance. Make all tests with the controller in the position for full speed.

Curves required:— Current and output, efficiency and output, power-factor and output, torque and output, and speed and output.